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STUDIES OF THE INNER SHELF AND COASTAL SEDIMENTATION ENVIRONMENT  
OF THE BEAUFORT SEA FROM ERTS-A

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<p><b>Abstract</b></p> <p>Landsat images and field observations were used to study sea ice processes and their relation to the geology and morphology of the Beaufort Sea continental shelf of Alaska and to study icings on Arctic rivers.</p> <p>Shearing periodically occurs between the westward moving pack ice (3 to 10 km/d) within the Pacific Gyre and the fast ice along the coast, forming major grounded shear and pressure ridges between the 10 to 40-m isobaths. Ridges occur in patterns conforming to known shoals. The zone of grounded ridges, here called stamukhi zone, protects the inner shelf and coast from marine energy and pack ice forces. Relatively undeformed fast ice grows inshore of the stamukhi zone. The boundary is explained in terms of pack ice drift and major promontories and shoals. Intense ice gouging, highly disrupted sediments, and landward migration of shoals suggest that much of the available marine energy is expended on the seafloor within the stamukhi zone.</p> <p>Naleds (products of river icings) on the North Slope are more abundant east than west of the Colville River. Their location, growth, and decay were studied from Landsat imagery. Many last through summer, serving as nuclei for new naleds. Naled occurrence is related to channel patterns, change in channel gradient, and springs. Naleds that grow through an entire winter mark locations of year round flowing fresh water, which is rare on the North Slope.</p>			
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DEVELOPMENT OF THE STAMUKHI ZONE AND ITS RELATION TO  
ARCTIC SHELF PROCESSES AND MORPHOLOGY, BEAUFORT SEA, ALASKA

by

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Larry Toimil  
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## ABSTRACT

Landsat-1 and NOAA satellite imagery for the winter 1972-73, and a variety of ice and seafloor data were used to study sea ice zonation and dynamics and their relation to bottom morphology and geology on the Beaufort Sea continental shelf of arctic Alaska.

In early winter the location of the boundary between undeformed fast ice and the westward drifting pack ice of the Pacific Gyre is controlled by major coastal promontories. Pronounced linear pressure- and shear-ridges, as well as hummock fields, form along this boundary and are stabilized by grounding, generally between the 10- to 20-m isobaths. Slippage along this boundary occurs intermittently at or seaward of the grounded ridges, forming new grounded ridges in a widening zone, the stamukhi zone, which by late winter extends out to the 40-m isobath. Between intermittent events along the stamukhi zone, pack ice drift and slippage is continuous along the shelf edge, at average rates of 3 to 10 km/day. Whether slippage occurs along the stamukhi zone or along the shelf edge, it is restricted to a zone several hundred meters wide and ice seaward of the slip face moves at uniform rates for tens of kilometers out into the pack ice drift without discernible drag effects.

A causal relation is seen between the spatial distribution of major ice ridge systems and offshore shoals downdrift of major coastal promontories. The shoals appear to have migrated shoreward under the influence of ice up to 400 m in the last 25 years. The seafloor seaward of these shoals within the stamukhi zone shows high ice gouge density, large incision depths, and a high degree of disruption of internal

sedimentary structures. The concentration of large ice ridges and our seafloor data in the stamukhi zone indicate that much of the available marine energy is expended here, while the inner shelf and coast, where the relatively undeformed fast ice grows, are sheltered. There is evidence that anomalies in the overall arctic shelf profile are related to sea ice zonation, ice dynamics, and bottom processes. A proposed ice zonation, including zones of (a) bottom-fast ice, (b) floating fast ice, (c) stamukhi, and (d) seasonal pack ice, emphasizes ice interaction with the shelf surface and differs from previous zonation.

Certain aspects of the results reported here are directly applicable to planned offshore developments in the Prudhoe Bay oil field. Properly placed artificial structures similar to offshore shoals should be able to withstand the forces of the ice, serve to modify the observed ice zonation, and might be used to make the environment less hostile to human activities.

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## INTRODUCTION

The presence of an ice cover over the continental shelves of the Arctic sea for eight to nine months of the year may imply to many marine geologists a period of quiescence, when the familiar processes controlling the sedimentological environment are dormant. Wind-driven currents are damped, sediment-laden river plumes are absent, and there is no wave activity. It is true that beaches in many areas of the Arctic are relatively stagnant for a large part of the year while they are protected by ice. But several recent reports dealing with the Beaufort Sea shelf point out that much of it has a dynamic environment year round, in which ice plays a dominant role (Reimnitz and Bruder, 1972; Reimnitz et al., 1972; Barnes and Reimnitz, 1974; Reimnitz et al., 1974; Reimnitz and Barnes, 1974; Walker, 1974).

This report describes a study of the winter shear zone, which lies between the Arctic pack ice and the fast ice, and its implications to shelf geology, morphology, and bottom processes.

The shear zone in the winter ice regime off northern Alaska occurs where ice carried along by the Pacific Gyre of the Beaufort Sea grinds against stationary fast ice on the inner continental shelf, resulting in the formation of pressure ridges, shear ridges, and hummock fields. Ice dynamics and extremely rough surface relief make the shear zone a formidable barrier to ice travel and to offshore petroleum exploration and development. Because many of the ridges survive the summer melt season and remain grounded, the shear zone also represents an obstacle to shipping. Much of the marine energy of the Beaufort Sea is expended

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within the offshore shear zone. We, therefore, are tempted to make an analogy between it and the surf zone of lower latitudes, although the processes and results obviously are very different.

Most studies of the shear zone have dealt with the problem of dynamics in the interior of large fields of sea ice, with ice deformational processes, and the resulting ice features. The overall interaction of the Arctic pack with the continent has received little attention. Because the present work is based largely on remote sensing without sufficient ground observations on the shear zone, and on shipboard studies during the summer, the conclusions drawn can only be considered preliminary. But the shear zone appears to be an important morphological and geological boundary on the continental shelf.

#### PURPOSE OF THE STUDY

The purpose of this report is to:

- (1) Delineate the shear zone of Alaska's north coast from Landsat-1 and NOAA-2 satellite imagery and to consider its relation to bathymetry and coastal configuration,
- (2) Study interactions between the pack ice drift and the stationary shore ice during winter,
- (3) Attempt to analyze the factors that control the early winter location of the shear zone and its subsequent shift seaward,
- (4) Relate shear zone processes to seafloor characteristics and bottom processes,
- (5) Speculate on possible side effects of the shear zone on the oceanographic and sedimentary environment, and to



(6) Speculate on some aspects of offshore construction in the shear zone.

#### BACKGROUND INFORMATION

For a general description of the continental shelf and coast in the study areas (Fig. 1) and its marine environment, including currents, tides, wind, ice drift, breakup, and river inflow, the reader is referred to Barnes and Reimnitz (1974) and Reimnitz and Barnes (1974). The background information given here is concerned mainly with the sea ice regime.

The sea ice on the continental shelf of the southern Beaufort Sea can be broadly divided into three zones (Kovacs and Mellor, 1974):

(1) a fast ice zone, extending from the coast to approximately the 20-m depth contour, (2) a seasonal pack ice zone that covers the outer shelf and continental slope, beyond which lies (3) the polar pack ice zone. Situated between the fast ice and seasonal pack ice zones, and generally considered part of the latter, is a fourth zone, the shear zone (Hibler et al., 1974; Kovacs and Mellor, 1974).

#### *Fast Ice Zone*

The term fast ice, as commonly used, refers to the ice near shore, which by virtue of being attached to the coast, to islands, and to shoals is relatively immobile for some unspecified time period during the winter. It generally consists mostly of seasonal ice grown in place, undergoes little deformation, and therefore is relatively smooth. But varying amounts of older ice may be incorporated, depending on its distribution during freezeup.

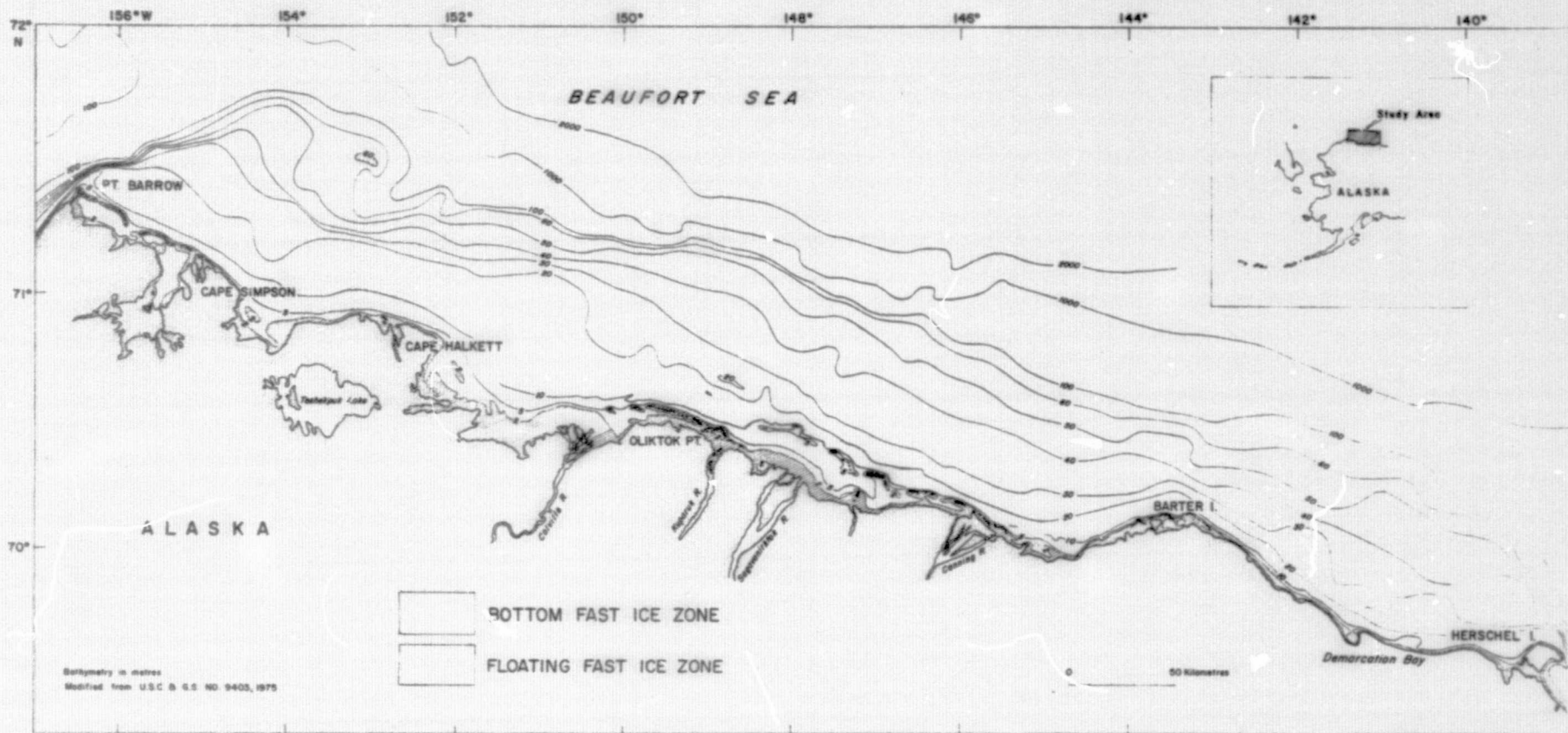


Figure 1. Study area showing bathymetry and place names. The extent of relatively undeformed fast ice was largely determined from Landsat-1 images between March 8 and April 21, 1973. Extent of 2-m-thick bottom-fast ice has been traced from bathymetric contours.

The seaward extent of the fast ice zone in the Arctic varies from one region to another, but is similar from year to year in a given area. In the eastern Canadian Arctic, its seaward boundary approximates the 180-m depth contour according to Jacobs et al. (1975). They use as the sole criterion that the ice be fast, and include any amount of newly deformed and multi-year ice. Disregarding ice types and morphology, most of the winter ice in the Canadian Archipelago, including that covering some very deep areas, may qualify as fast ice (Dehn, 1974, p. 229). In the White Sea the boundary lies along the 10-m depth contour, and along the Siberian Arctic coast along the 25-m line (Zubov, 1945). In the Beaufort Sea east of the MacKenzie Delta the fast ice zone extends to the 20-m depth contour, while immediately west of the delta there may be no true fast ice, but rather "quasi-landfast ice" as described by Cooper (1974). North of Alaska the 20-m depth contour is commonly considered to be the seaward limit of fast ice (Weeks et al., 1971; Burns and Harbo, 1972; Kovacs and Mellor, 1974; Reimnitz and Barnes, 1974). Here the boundary is marked by a change from relatively undeformed, smooth ice inshore to highly deformed ice offshore. Stringer (1974), studying the western Beaufort Sea, subdivided the fast ice zone and added the term "attached ice", "which is a floating ice field temporarily attached to the shorefast ice. Many of the authors cited and still others, including us, see problems with the definition of fast ice, and Cooper (1974) suggested that the terminology should be changed.

Kovacs and Mellor (1974) give a general description of the growth, seasonal variability in extent, deformational features, and behavior of

the fast ice applicable to our study area. This ice can contain pressure ridges, shear ridges, and hummock fields, which form mainly in early winter when new ice is still thin. Deformation of the fast ice decreases from mid-winter to spring, as it approaches maximum thickness of about 2 m, and as its outer edge becomes stabilized by grounded pressure ridges and older ice (Stringer, 1974; Kovacs and Mellor, 1974; Reimnitz and Barnes, 1974). Because the outer edge extends to the 10 or 20 m depth contour, much of the fast ice is floating, and fluctuates with astronomical and meteorological tides. In the Alaska Beaufort Sea there are, however, extensive areas (up to 10 km wide) landward of the 2-m isobath where ice is resting on the seafloor at the end of the winter. This ice has been called bottom fast ice (Reimnitz and Barnes, 1974). At and slightly seaward of the 2-m depth contour the ice is often marked by tidal cracks.

#### *Seasonal Pack Ice Zone*

This zone, which also has been called the Offshore Province (Weeks et al., 1971), extends from the fast ice boundary seaward for 100 to 200 km, which in the study area is in the vicinity of the base of the continental slope. The ice in this zone is generally unstable and mobile, and is largely composed of first-year ice that is extensively deformed (Weeks et al., 1971; Kovacs and Mellor, 1974). The zone lies within the Pacific Gyre of the Beaufort Sea (Campbell, 1965), which rotates clockwise. Thus, the ice moves generally westward, with mean net long-term winter drift of about 2 to 2.5 km/day (Coachman and Barnes, 1961). A drift rate of 3 km/day was recently calculated from studies of remote sensing imagery taken during April, 1973 in

this area (Campbell et al., 1975). A short-term maximum drift rate of 50 km/day has been reported by Hnatiuk and Johnston (1973).

Studies of satellite imagery obtained north of Alaska have led to the conclusion that the ice within the Pacific Gyre behaves as a relatively cohesive mass, with boundary slippage occurring in a 50-km-wide zone immediately seaward of the fast ice (Crowder et al., 1973; Hibler et al., 1974). Near the fast ice the seasonal pack ice drift velocity is thought to be reduced by drag (Kovacs and Mellor, 1974).

#### *Shear Zone.*

The zone of differential ice motion, or slippage, along the fast ice boundary has been generally referred to as the shear zone. It is characterized by large shear ridges, pressure ridges, and hummock fields (Kovacs and Mellor, 1974). Certain ice observations made by early explorers in the Beaufort Sea fit this general concept, in that the roughest ice terrain was encountered just seaward of the smooth fast ice of the coastal zone (Stefansson, 1921). A winter shear ridge field 16 km long was reported by Stockton (1880) to be grounded in 24 m of water north of Cross Island, in the middle of our study area. A grounded pressure ridge was measured by Stefansson (1921) to be 23 m high, and he mentions many higher ones grounded in up to 39 m of water off Banks Island. Zubov (1945) reports that "stamukhi" - grounded sea ice formations formed as a result of "ice heaping" - occur over a distance of about 500 km along the 20 m isobath east of the New Siberian Islands. Recent studies by Klimovich (1972) show that in the inner 5 km of the shear zone, adjacent to the fast ice, ridges are up to 20 percent higher

than in the outer part. Results from other studies showing the increased density, height, and draft (keel depth) of ridges near the coast have been summarized by Kovacs and Mellor (1974). Stringer (1974) shows the relation of major shear events in the winter ice of this area to bathymetry. Reimnitz and Barnes (1974) report a sudden increase in ice gouge density seaward of the fast ice edge, which they relate to shear zone processes, and Barnes and Reimnitz (1974) find that internal sedimentary structures seen in box cores show the effects of physical disruption by grounded ice in the inner part of the shear zone.

#### METHODS OF STUDY

Our study is heavily based on interpretations of Landsat-1 and NOAA-2 satellite imagery of 1972-73. Coupled with these data are a variety of observations gathered during ice-based and shipboard operations. Methods used are outlined by Barnes and Reimnitz (1974) and Reimnitz and Barnes (1974). More recent side-scan sonar and precisely controlled bathymetric surveys conducted in 1975 have also been incorporated into this study.

Utilization of Landsat-1 repetitive imagery over regions of high latitude has the advantage of image overlap of successive satellite passes. Cloud cover permitting, we were able to trace particular ice features for three consecutive days every 18 days.

In the Landsat images the shear zone is generally characterized by pronounced lineations in the ice cover that approximately parallel the shore. Shear ridges are common features along the northern Alaskan coast and are often tens of kilometers long (Kovacs and Mellor, 1974),

whereas pressure ridges are irregular and randomly distributed (Anderson, 1970). Therefore, we interpret many of the light-colored linear features seen in the imagery as shear ridges. Narrow leads and refrozen leads are also often linear but are darker than the thicker ice. Comparing ground observations with the imagery we find that linear zonations less than 30 m wide can be detected under favorable conditions.

## RESULTS

### *Remote Sensing*

Landsat-1 imagery discussed below covers the period from freeze-up in the fall of 1972 through the breakup in the summer of 1973. No imagery was obtained during the Arctic night from November through February.

The onset of winter and formation of a new ice cover are shown in Figure 2. This image, taken on October 4th, 1972 (1073-21223) covers an area of about 180 km square. The coastal plain is blanketed by thin snow, and most of the rivers have stopped flowing. New ice is mainly seen on the shallow inner shelf, where salinity is lower and water cools faster than offshore. A light southwesterly wind is moving the thin ice obliquely offshore, where in many spots it is trapped by islands. The total absence of old ice on the shelf, confirmed by Nimbus 5 microwave images for December 16, 1972 and February 10, 1973 (Campbell et al., 1974) is significant to our later discussion. Conditions therefore differed considerably from those of the previous years, in which large numbers of ice island fragments were grounded on the shelf (for example, Breslau et al., 1971). The last remnants of these fragments were seen in Landsat imagery of August 1972.



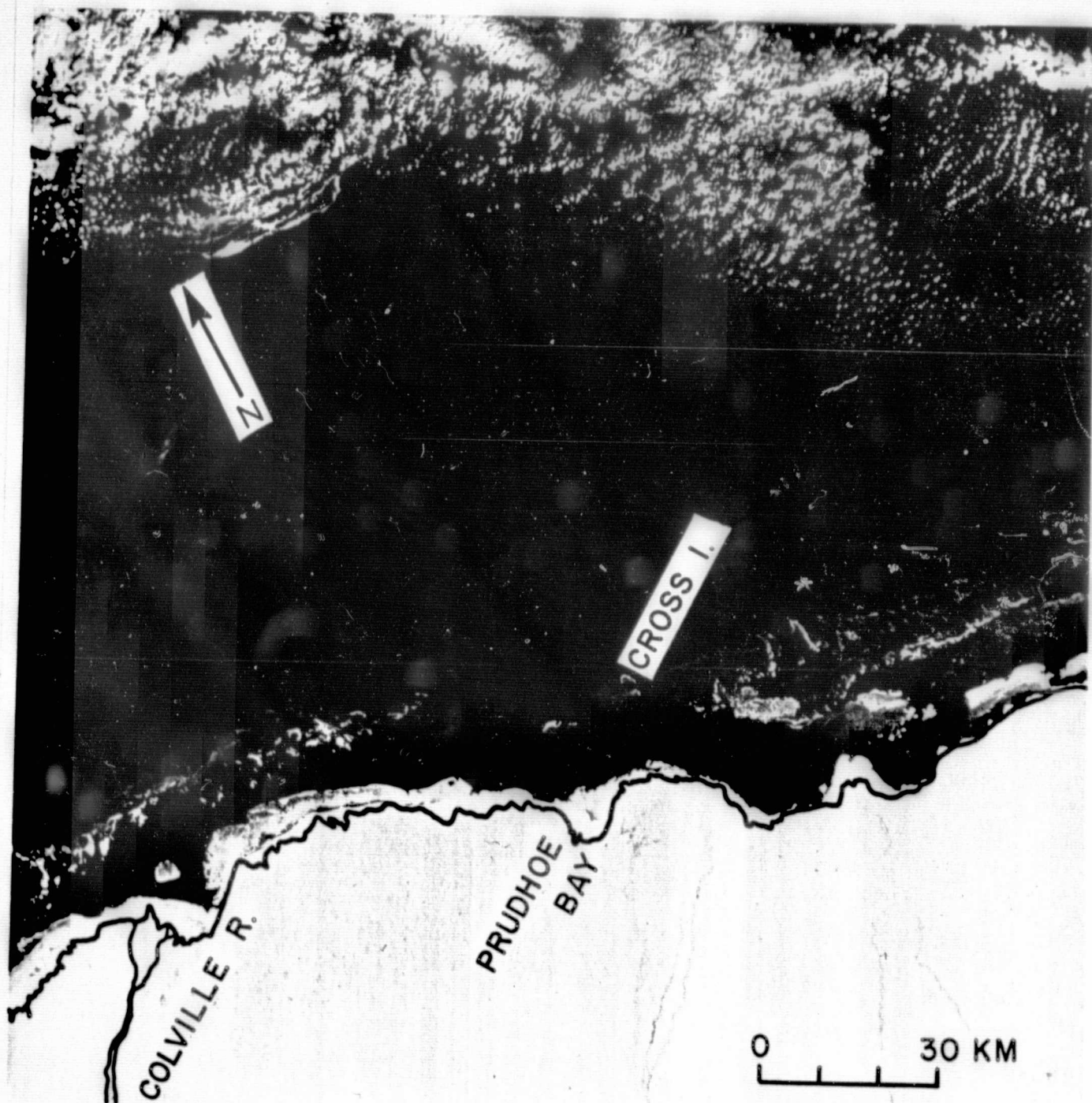


Figure 2. October 4th, 1972 Landsat-1 image showing formation of new ice on the shallow inner shelf, and drift accumulation against south side of barrier islands. No old ice is visible within the 100 x 100 nautical miles covered by the image (1073-21223).

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Early 1973 Landsat-1 images of the Beaufort Sea were recorded from March 8 to April 21. At this time the fast ice along the coast between Herschel Island in Canada and Point Barrow, Alaska (Fig. 1) is well stabilized and approaching its maximum thickness of about 2 m. The outer boundary of the relatively undeformed fast ice adjacent to the coast is generally marked by pronounced lineations in the Landsat-1 images. These are interpreted as shear ridges formed earlier during the winter. The first pronounced shearline near the coast, or the first marked change in ice appearance from uniform to irregular, was mapped as representing the seaward boundary of the relatively undeformed floating fast ice (seaward extent of stippled pattern in Fig. 1). In some areas it was difficult to decide where to place the boundary. In these cases later images, when ice features were enhanced by melting of the sea ice surface, were used. Comparing the various images obtained along the coast from early March to ice breakup in July we found no new major ice deformational features forming within the floating fast ice zone shown in Figure 1. The cross-hatched area near the coast in Figure 1 represents regions in which water depth is less than 2 m, where the fast ice is resting on the seafloor at the end of the winter.

The most detailed analysis of ice processes was done in the area between Cape Halkett and Canning River, where our previous seafloor studies were concentrated. In this area March 14 through 16 images (nos. 1234-21175, 1235-21241, 1236-21297) show that the most recent events were the formation of a pronounced lead trending irregularly across the shelf,

(Fig. 3,B) and one trending parallel to the coast (Fig. 3,A). Both are refrozen but the ice is still thin, as interpreted from its relatively dark color. Matching the sides of the shore-parallel lead (A) indicates that the pack ice was displaced eastward relative to the fast ice landward of the lead by 2 km. Wind records for the North Slope suggest that this may have occurred on March 7 (Stringer, 1974) during relatively strong westerly winds. Because shearing along the shore-parallel lead was associated with the ice movement, this feature may be called a shearline. It is located seaward of the undeformed fast-ice edge (Fig. 1), indicating accretion of the fast ice zone.

The shore-parallel shearline and the lead trending obliquely across the continental shelf were well preserved between March 14-16 and April 1-3 when new images were obtained in the area (nos. 1252-21175, 1253-21233, 1254-21292). No changes could be detected by matching these images and the earlier ones to coastal features, and comparing the location and configuration of ice features. This match is accurate to within about 300 m. Thus, all ice across the width of the shelf moved less than 300 m, if any, during a 20-day period.

Early April imagery shows a large lead (D) and an active shearline (C) barely seaward of and parallel to the edge of the continental shelf (stippled area, Fig. 3). The shearline may have been active for several weeks, but no imagery is available to confirm such activity. Matching particular ice features seen in the images of April 1 and 2, a 4 km/day westward displacement of the pack ice relative to the stationary ice sheet over the shelf is indicated. The rate of ice movement was uniform through a 24-km-wide zone seaward of the shearline,

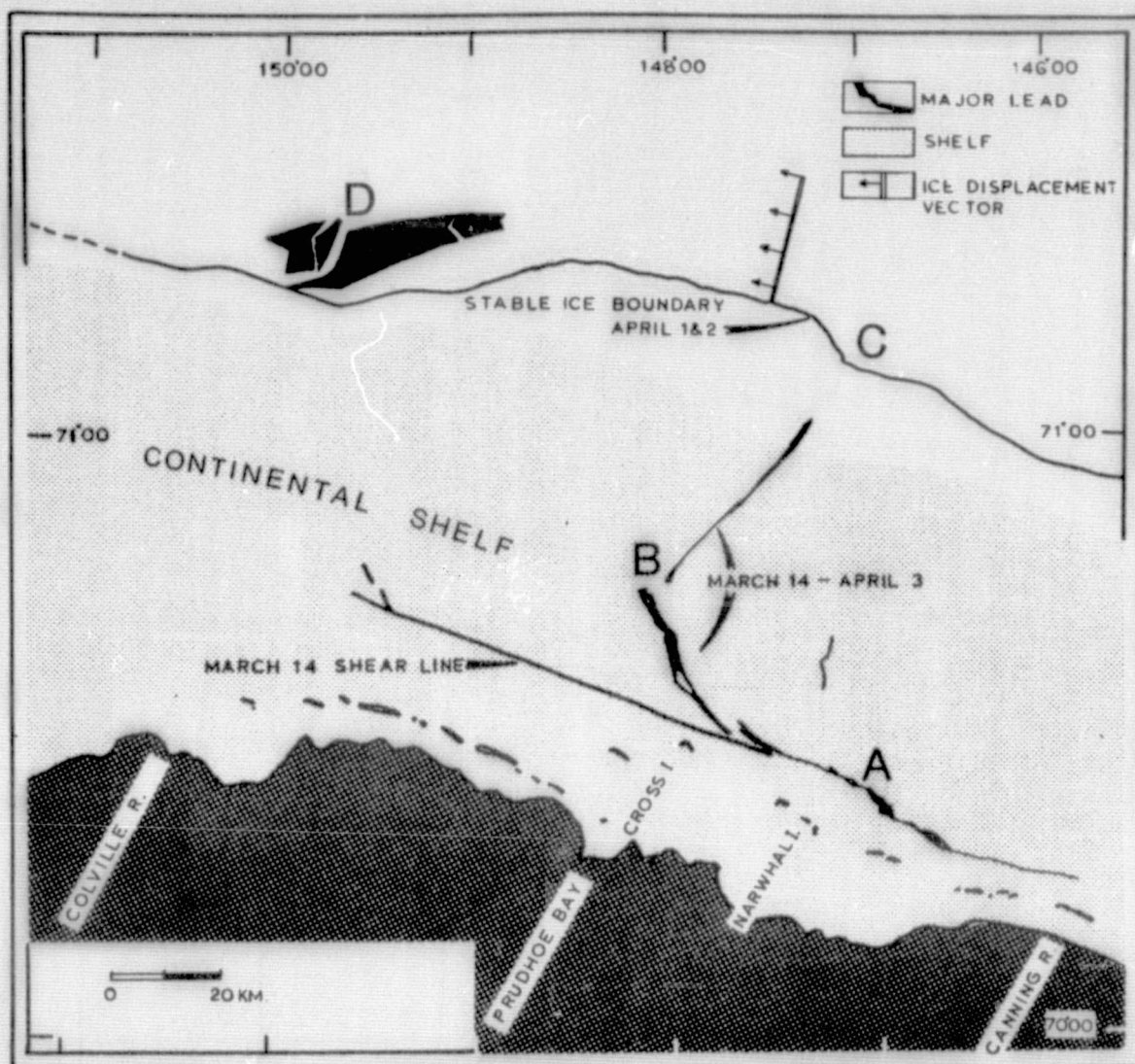


Figure 3. March 14 through 16, 1973 Landsat images (nos. 1234-21175, 1235-21241, 1236-21297) show a recent shore-parallel lead (A) and roughly shore-normal lead (B). The configuration of (A) indicates that the ice seaward has been displaced eastward by 2 km relative to the stationary ice. In early April (Landsat image nos. 1252-21175, 1253-21233, 1254-21292), an active shearline (C) paralleling the shelf edge was associated with westward pack ice displacements of 4 km/day. The displacement, shown by length of arrows, was uniform through a 24-km-wide zone seaward of the slip face.

as indicated by the length of the ice-displacement vectors on Figure 3. No drag effects along the shearline were noted.

Visible-band NOAA-2 satellite imagery taken during the same time period permits a large-scale view of ice conditions in the entire Beaufort Sea. Figure 4 is an example of a small portion of such an image, taken on April 5, 1973. The active shearline seen in the Landsat imagery of April 1-3 along the shelf edge (Fig. 3,C) can be seen in the NOAA image. It also shows a pronounced linear lead (traced in Fig. 5) extending hundreds of kilometers into the Arctic Ocean. Using this lead as a marker, large-scale pack ice movement and its relation to the associated shearline along the Beaufort Sea shelf was monitored.

Figure 5 shows the location of the major lead on NOAA-2 imagery of March 26, March 31, and April 1. These images are somewhat distorted but could be matched with a fair degree of confidence to northern Alaska. The wide place in the shearline along the edge of the continental shelf is the large open lead (40x15 km) seen in Landsat images at this time (Fig. 3,D). The large dots are identifiable points seen along the lead in all three images. This compilation shows that the pack ice in a 350-km-wide zone north of the shearline is moving westward rather uniformly at about 10 km/day. The lead seems to be little affected by drag along the shearline, which roughly corresponds to the edge of the shelf. This confirms the more detailed Landsat studies shown in Figure 3.

There is no useable Landsat-1 imagery in the study area between April 3rd and May 26-27. May 27 ice conditions are shown in Figure 6 (no. 1308-21290). The pronounced coast-parallel shearline and coast-



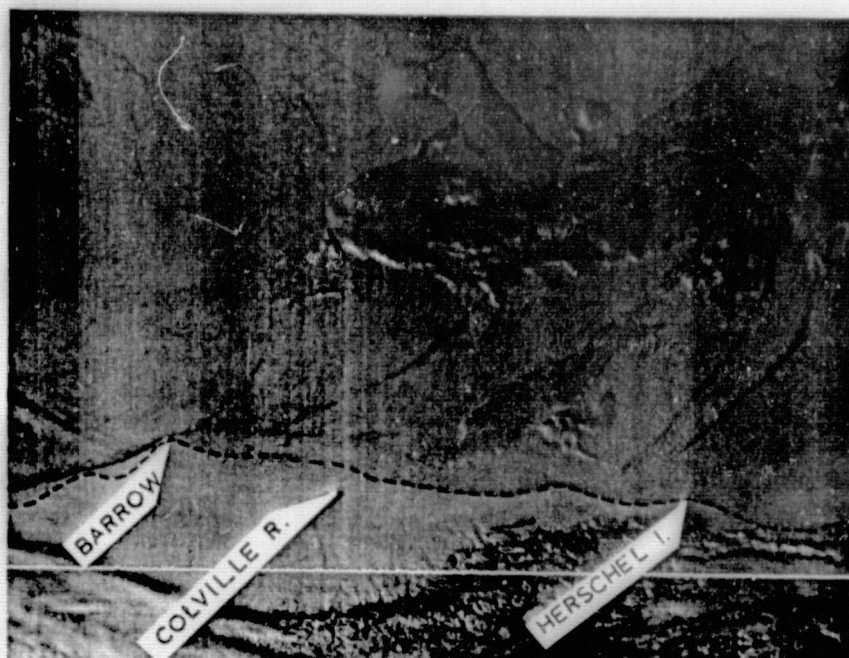


Figure 4. Visible-band NOAA-2 satellite image taken April 5, 1973. The large (40 x 15 km) polynya shown in Figure 3(D) can be identified on this image. A curvilinear lead extends from the shelf-parallel shearline for hundreds of kilometers into the Arctic Ocean.

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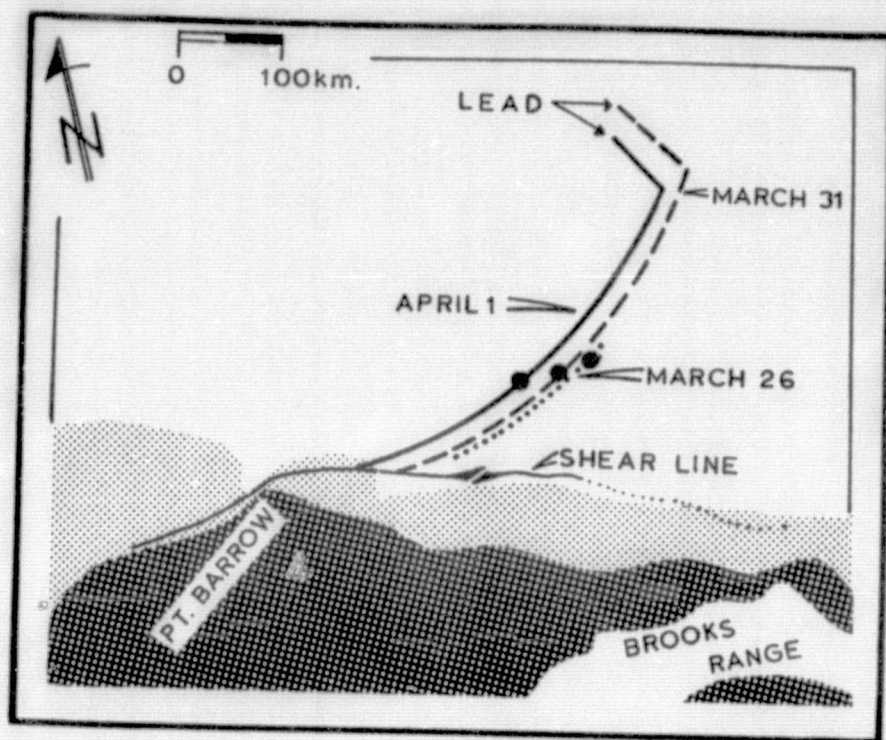


Figure 5. Comparison of the location of major lead seen on NOAA-2 imagery March 26, March 31, and April 1, 1973. The large dots mark points along the lead identifiable in all three images. The pack ice in a 350-km-wide zone north of the coast-parallel shearline moved uniformly at about 10 km/day.

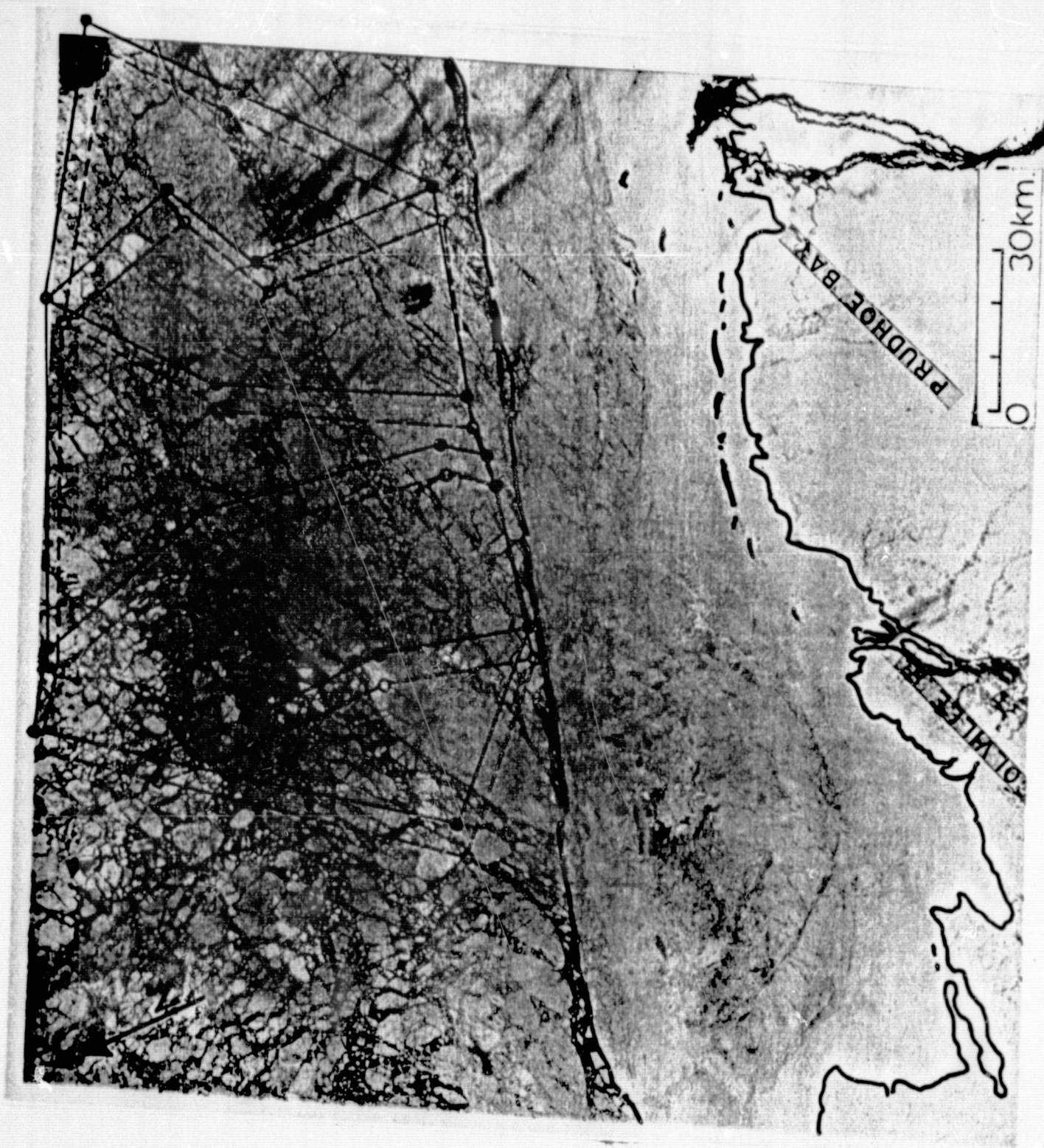


normal lead seen in images from March 14 to April 3 have disappeared. These features may have been destroyed by deformation or displacement of the entire ice canopy seaward of the early winter shearline (Fig. 1), leaving only the true fast ice landward of this line intact. Such deformation is suggested by the formation of short, irregular, refrozen, northeast-striking leads about 10 km west of Cross Island (Fig. 6), which have been previously noted by Stringer (1974). The lead and shearline under discussion may also have been masked by new or drifting snow. A new pronounced coast-parallel lineation not present on April 3 is seen in the image of Figure 6. This lineation can be traced westward across Harrison Bay, where it bulges northward roughly following the 20-m depth contour, far seaward of the early winter shearline. This bulge was pointed out by Stringer (1974) using the same imagery and by Burns and Harbo (1972). It will be discussed again below.

The onset of summer, marked by river flooding of the fast ice in the eastern part of the image area (Sagavanirktok River), is evident in Figure 6. A strongly linear active shearline can be seen on this and the previous day's image. Overlaying these images, we find that the ice landward of the shearline is immobile. Seaward of the line it is moving westward. Comparing the location of identifiable ice features during this 24-hour period, indicated by dots on Figure 6, indicates ice displacement westward at a rate of 6 km/day. Close to the shearline the ice drift vectors are parallel. Further seaward a small onshore component is indicated, implying that some portion of the ice canopy is used up in the formation of shear and pressure ridges. The entire ice canopy out to 90 km from the shearline is highly fractured but apparently

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Figure 6. May 27, 1973, Landsat image (no. 1308-21290) showing recent irregular refrozen cracks about 10 km west of Cross Island produced by ice deformation along early winter shearline. A pronounced coast-parallel, active shearline bulges seaward along the 20-m isobath across Harrison Bay. Comparison with ice features identifiable on previous days image reveals uniform displacement of 6 km/day over the shown strain network extending some 90 km seaward of the shearline. No drag effects near the stationary ice/drifting pack ice boundary are visible.



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moving as a rather coherent mass. The westward displacement rates do not seem to be affected by drag along the shearline, but are instead somewhat higher there than further offshore.

Visible-band NOAA-2 satellite imagery can be used during this time period to study large-scale ice movement in the Arctic Ocean north of Alaska. The images of April 5th and May 27th (Fig. 7) show the long lead discussed earlier and presented in Figures 4 and 5. The projection of these images is not the same as that of the others, resulting in a different distortion of the Earth's surface. But their match to the continent is more reliable and the ice displacement vectors therefore more accurate. The westward displacement of the lead during the 52 days preceding the 27th of May ranges from 160 km (3 km/day) near the continent to 80 km (1.5 km/day) at a point 450 km seaward of the coast.

The next Landsat images in the study area cover the period from June 13 to June 15. At that time no coast-parallel shear could be seen on the continental shelf, and east of Oliktok Point all ice on the shelf was stationary during the two-day period. West of Oliktok Point, ice was moving obliquely onshore toward Cape Halkett along a conspicuous lead. This movement is clearly seen seaward of the 50-m isobath but apparently did not affect the shearline first seen along the central shelf on May 26.

From the above discussion of Landsat and NOAA-2 images, it is apparent that shear events along the inner and central shelf are intermittent, whereas westward ice drift along the shelf edge is continuous. This implies that shearing occurs seaward of the shelf edge between the times of shear events on the shelf, as was seen in early April.

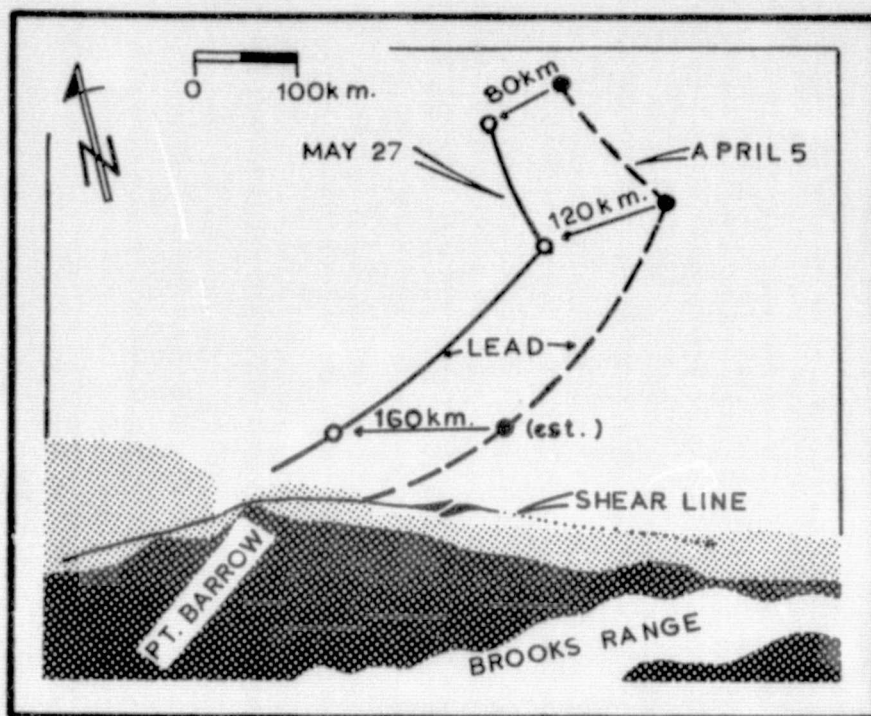


Figure 7. Tracing from NOAA-2 visible-band images of April 5 and May 27, 1973, showing westward displacement of long lead seen in Figures 4 and 5. During the 52-day period displacements ranged from 160 km (3 km/day) near the continent to 80 km (1.5 km/day) at a point 450 km seaward of the coast. Differences in displacements are considered representative of points at various distances from the center of the clockwise rotation within the Pacific Gyre.



Figure 8 shows the initiation of sea ice breakup, as seen in the following data cycle (June 30, no. 1342-21170, July 2 and 3, nos. 1344-21283, 1345-21342). At this time of the year, meltwater drains from relief features, leaving the ice and snow white, and collects on smooth ice, enhancing image definition of morphological features. East of Oliktok Point, the ice is still intact and no active shearline is seen on the shelf. Preserved shear features are clearly visible. West of Oliktok Point, the ice is beginning to break up and move westward close to the Colville Delta and along the outer shelf. However, in a 15-km-wide zone bulging seaward across Harrison Bay along the 20-m isobath, and coinciding with major shear events of late winter, the ice remains intact.

Figure 9 shows a strip of U-2 photographs, taken from an altitude of 20,000 m on June 21, 1974. This strip, extending from Prudhoe Bay, north, shows the various ice zones and features discussed above in great detail. The sea ice morphology is similar to that of the previous year, with the relatively undeformed fast ice extending a short distance beyond Reindeer Island. It is followed by a zone of highly deformed and probably grounded ice in the stamukhi zone, and the mobile ice beyond.

The most pronounced linear ice features, taken mainly from the early July 1973 Landsat imagery, which records major shear events along the inner part of the shear zone, are shown in Figure 10. The resultant ice drift vectors, implying the general direction in which the pack ice is moved along the shearlines, and the dominant wind direction, are also shown, along with the locations and approximate extent of charted shoals (hachured areas).

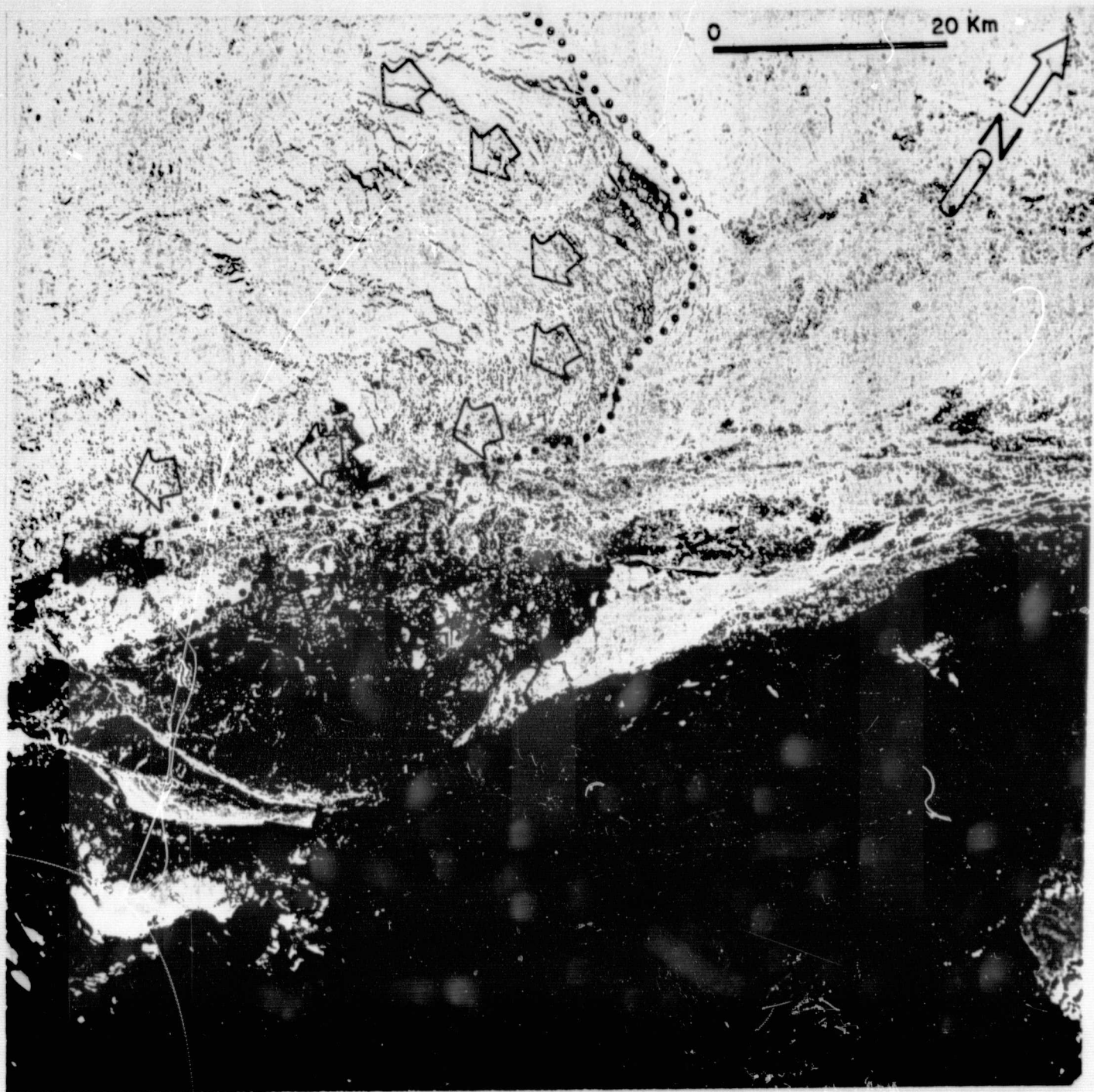
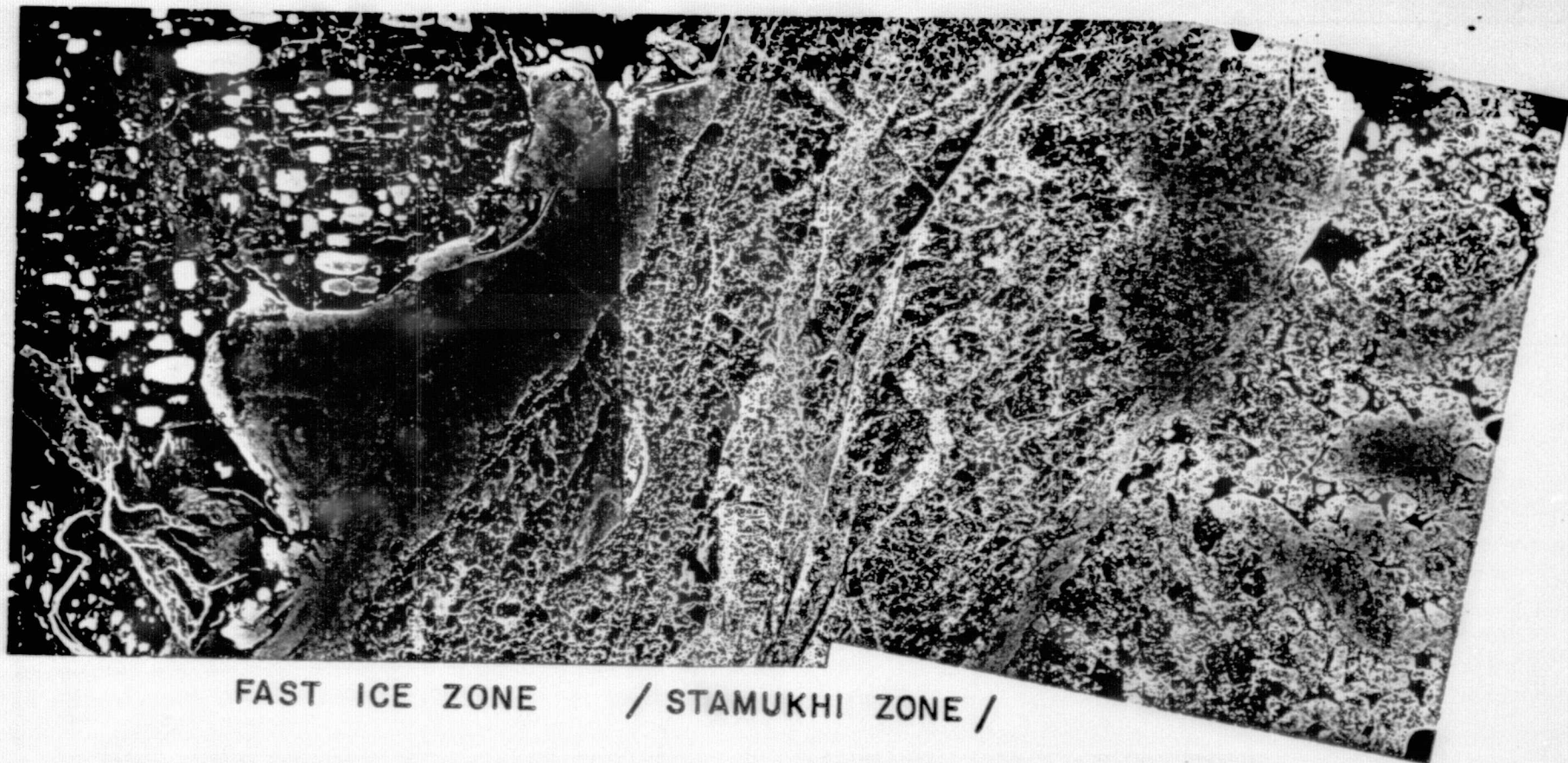


Figure 8. July 2, 1973 Landsat-1 image (1344-21283) showing initiation of sea ice breakup. Ice on inner and outer shelf west of Oliktok Point is breaking up and moving westward. A 15-km-wide zone coinciding with zone of major shear events during winter remains intact. This breakup pattern suggests the presence of stamukhi along the 20-m isobath.

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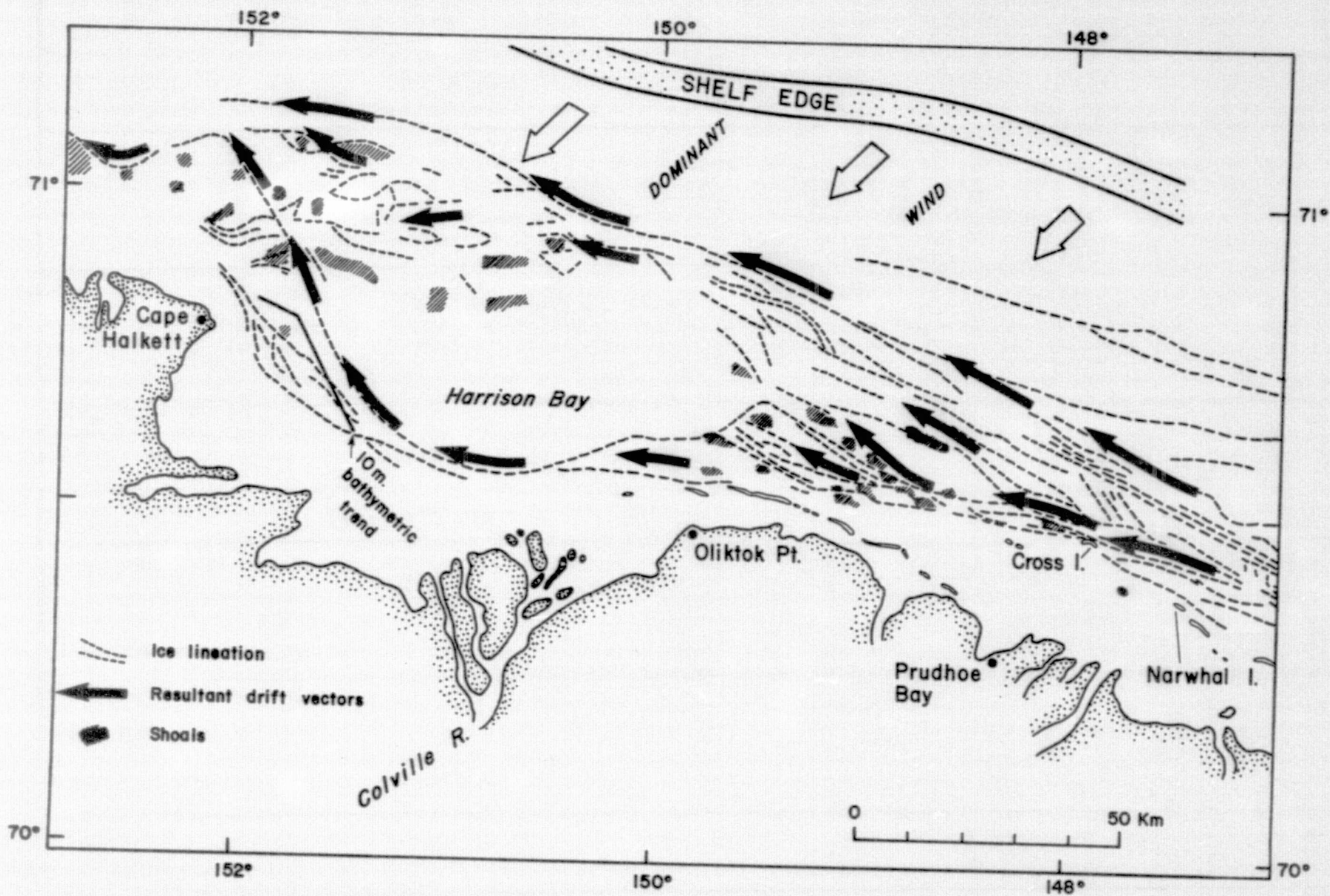


FAST ICE ZONE / STAMUKHI ZONE /

Figure 9. Mosaic of U-2 color infrared photos taken from an altitude of 20,000 m on July 21, 1974. Flightline extends north from Prudhoe Bay. Sea ice morphology is similar to that of 1973. Smooth fast ice, lightly deformed shortly after freezeup, extends to just beyond Reindeer Island, followed by strongly lineated and rough ice in the stamukhi zone and a zone of mobile ice on the outer shelf.

16 a

Figure 10. Generalized model of ice drift within area of detailed study, showing predominant movement of pack ice along well-defined shearlines, dominant wind direction, and location of charted shoals (hachured areas). Note striking correlation between distribution of shoals and major ice lineations traced from Landsat images, which represent shear ridges, pressure ridges, and linear hummock fields.



The striking correlation between the distribution of shoals and ice lineation (that is, shear ridges, pressure ridges, and linear hummock fields which are all known to have considerable draft) suggests that the ice is interacting with the seafloor.

### *Summer Ice Observations*

During summer, grounded ice is commonly found on offshore shoals (Reimnitz et al., 1972, 1974). This ice generally appears to be of pressure-ridge origin, with sail heights of 5 to 8 m, keel depths of at least 10 m, and is elongated parallel to isobaths. Drifting smaller floes frequently accumulate along the seaward side of these grounded floes, which act as fences. Sometimes the grounded ridges occur in long lines paralleling isobaths, marking a distinct boundary between scattered ice on the inner shelf and tightly packed ice on the central shelf. Figure 11 is an example of such a boundary, photographed from the air northeast of Barrow on August 31, 1975. Such boundaries roughly correspond with the seaward boundary of the fast ice. It closely approaches major promontories and offshore islands, as at Herschel Island, Barter Island, and Cross Island. North and east of Cross Island, large stationary ice floes in average years block small-boat passage offshore.

A continuous belt of apparently grounded floes was observed along nearly the entire Alaskan Beaufort Sea coast by W. Stanley Hugget (Ocean and Aquatic Affairs, Dept. of Environment, Canada) in late August, 1966 (personal commun., 1974). This belt straddled the 18-m isobath, separating relatively ice-free waters on either side, and was impenetrable



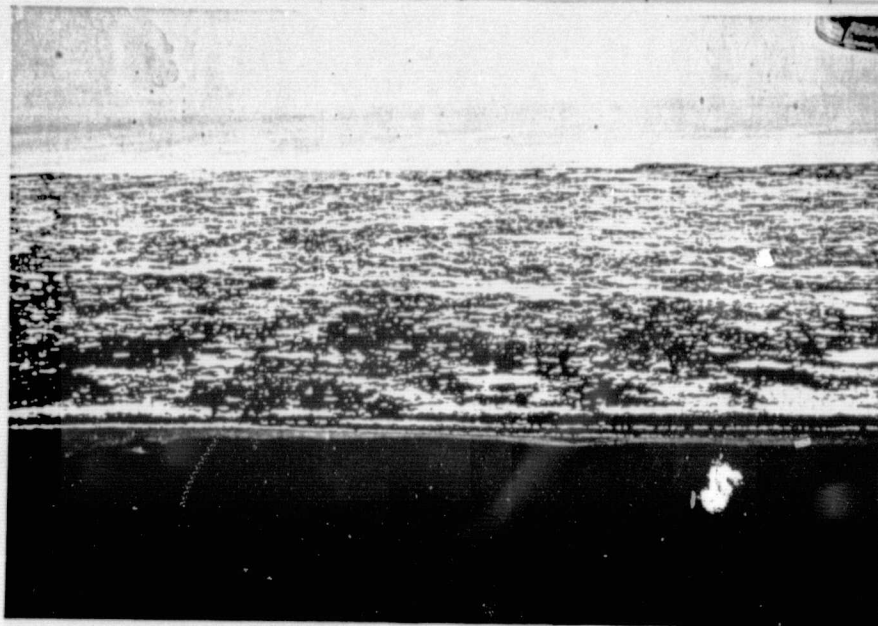


Figure 11. Oblique aerial photograph taken northeast of Pt. Barrow on August 13, 1975. Grounded ridges (stamukhi) occur along lines paralleling isobaths (upper fourth of photo), marking a distinct boundary between scattered ice on inner shelf (central part of photo) and tightly packed ice beyond.



Figure 12. June 1970 photograph of ice push features on Narwhal Island. Such ice push features and associated beach deformation recur annually on major coastal promontories such as Narwhal Island and Cross Island that are exposed to shearzone ice dynamics.

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to small vessels. Its location again roughly corresponds with the zone of major ice ridges formed along the seaward boundary of the undeformed fast ice (Fig. 1).

### *Interaction of ice and continental margin*

The relation between pronounced ice lineation preserved by the end of the winter (Figs. 8 and 10) and shelf bathymetry, the stabilizing effect of ice ridges on the fast ice, and the location of grounded ice in summer, indicate that the zone broadly straddling the 20-m isobath is the locus of the strongest interaction between the ice pack and the seafloor.

Ice ridging is best defined, most concentrated, and closest to land off Narwhal and Cross Islands. Downdrift (westward) from Cross Island ridges spread in a widening zone, following the pattern of shoals at increasing distance from shore. On the seaward-facing beaches of Narwhal and Cross Islands, where ridges are formed close to shore, one can observe year after year the effects of pronounced ice push and remnant ice piles from the previous winter. Figure 12 is a photograph of ice deformation on Narwhal Island taken in June 1970. Argo and Reindeer Islands, downdrift of and somewhat protected by Cross Island, are relatively little affected by ice push. Still farther downdrift and several kilometers from the major ice ridge systems, beaches are little affected by winter ice push. Figure 13 is a typical example of such a barrier island beach, as photographed in May 1972 on Long Island. The fast ice rests smoothly against the beach face and seafloor out to the vicinity of the 2-m isobath, which is marked by several tidal cracks. Beyond the cracks the fast ice is floating

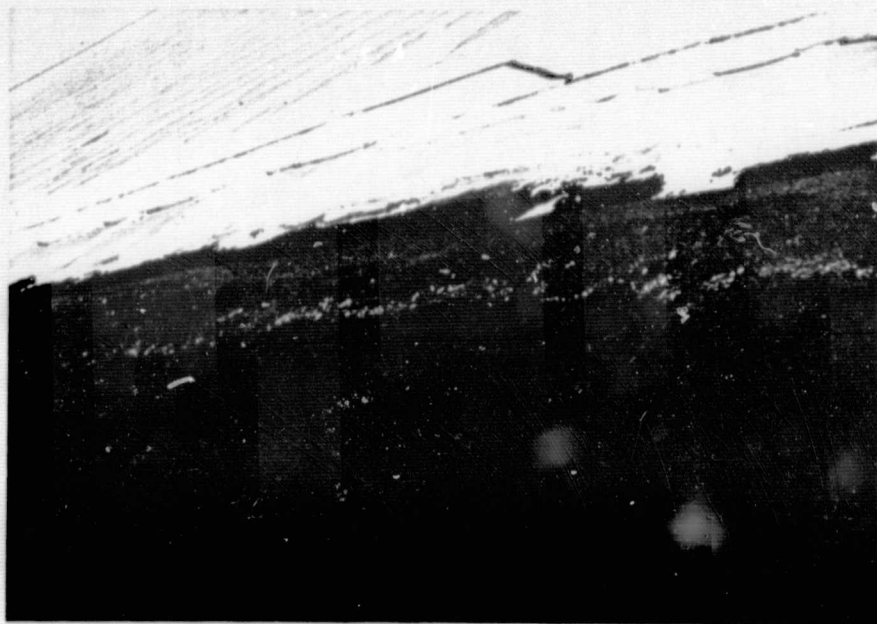


Figure 13. Example of barrier island beaches that lie downdrift of major promontories and landward of shoals. Photographed May 1972 on Long Island. The 2-m isobath seaward of beach is marked by characteristic tidal crack in relatively smooth fast ice.

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and undeformed out to the first major shoals, discussed later. Still farther westward, across Harrison Bay, the undeformed fast ice stretches for many kilometers from shore, protecting the coast. Nearshore bottom profiles, off Cross Island, where the shear zone impinges on the coast, and Spy Island, where it lies some distance offshore, are very different (Fig. 14). Spy Island (Fig. 15), typical of regions protected from the drifting ice pack, has a gentle and smooth seaward slope, while the bottom at Cross Island is steep and irregular.

The inner shelf bathymetry of the central part of our study area is shown in Figure 15, as surveyed from 1949 to 1951. During the summer of 1975, the U.S. Geological Survey's R/V *Karluk* was used to run bathymetric surveys across some of the shoals. With a Del Norte Trisponder system and shore control stations at the established bench marks indicated by triangles in Figure 15, the navigational control for the surveys was accurate to within 5 meters. From the 1949-51 and 1975 surveys a comparison of certain ridge cross sections and their locations was made. These are presented in Figure 16, with individual profiles keyed to Figure 15 by letters A through H. The 1949-51 bottom configuration is represented by the dashed line, the new configuration by a solid line, which also shows micro-relief due to ice gouging.

The shoals are very subtle features, considering that the vertical exaggeration is about 1:30. Shoals A and B, located north of Spy Island, are about 3 m high. The seaward one (A) has shifted landward by about 200 m, retaining its shape, while the landward one (B) shifted only 120 m, but increased in size. Among the shoals north of Cottle Island, C is closest to shore. Considering that the dashed line represents an



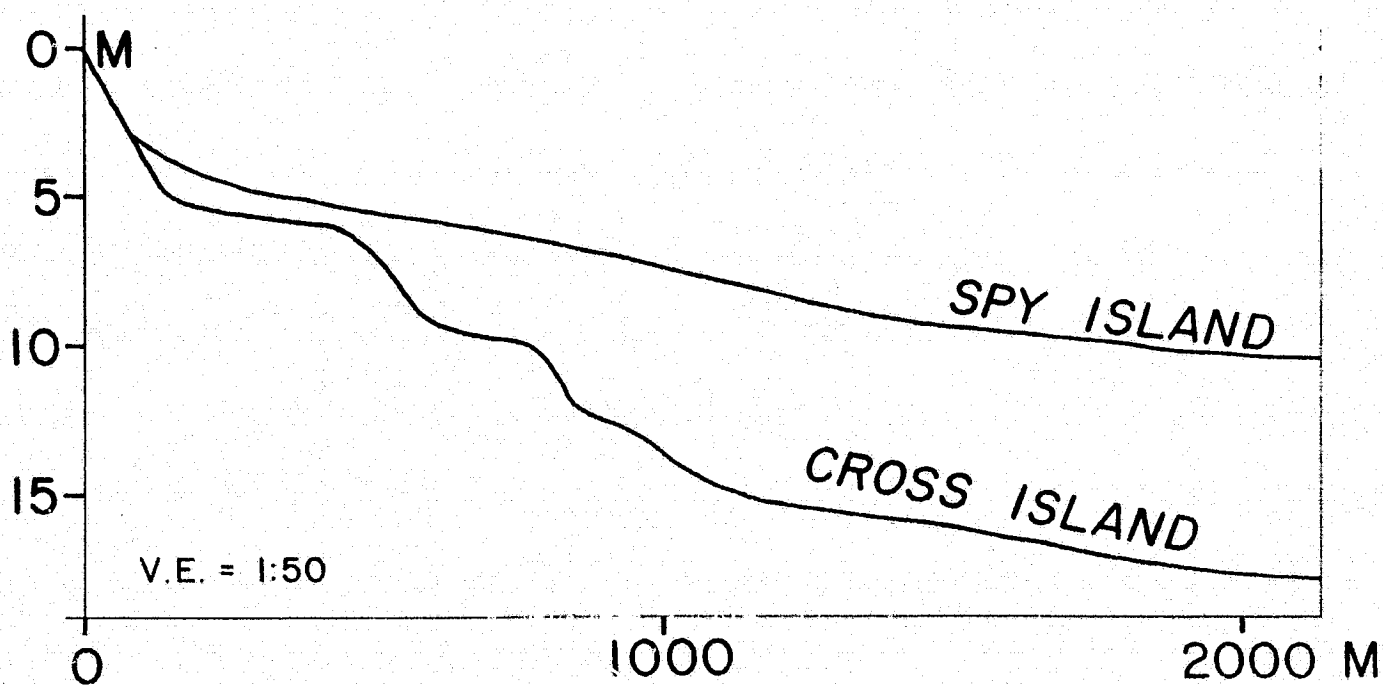


Figure 14. Comparison of bottom profiles off Cross Island, where the shear zone impinges on the coast, and Spy Island, (Fig. 15), protected by streaks on offshore shoals.

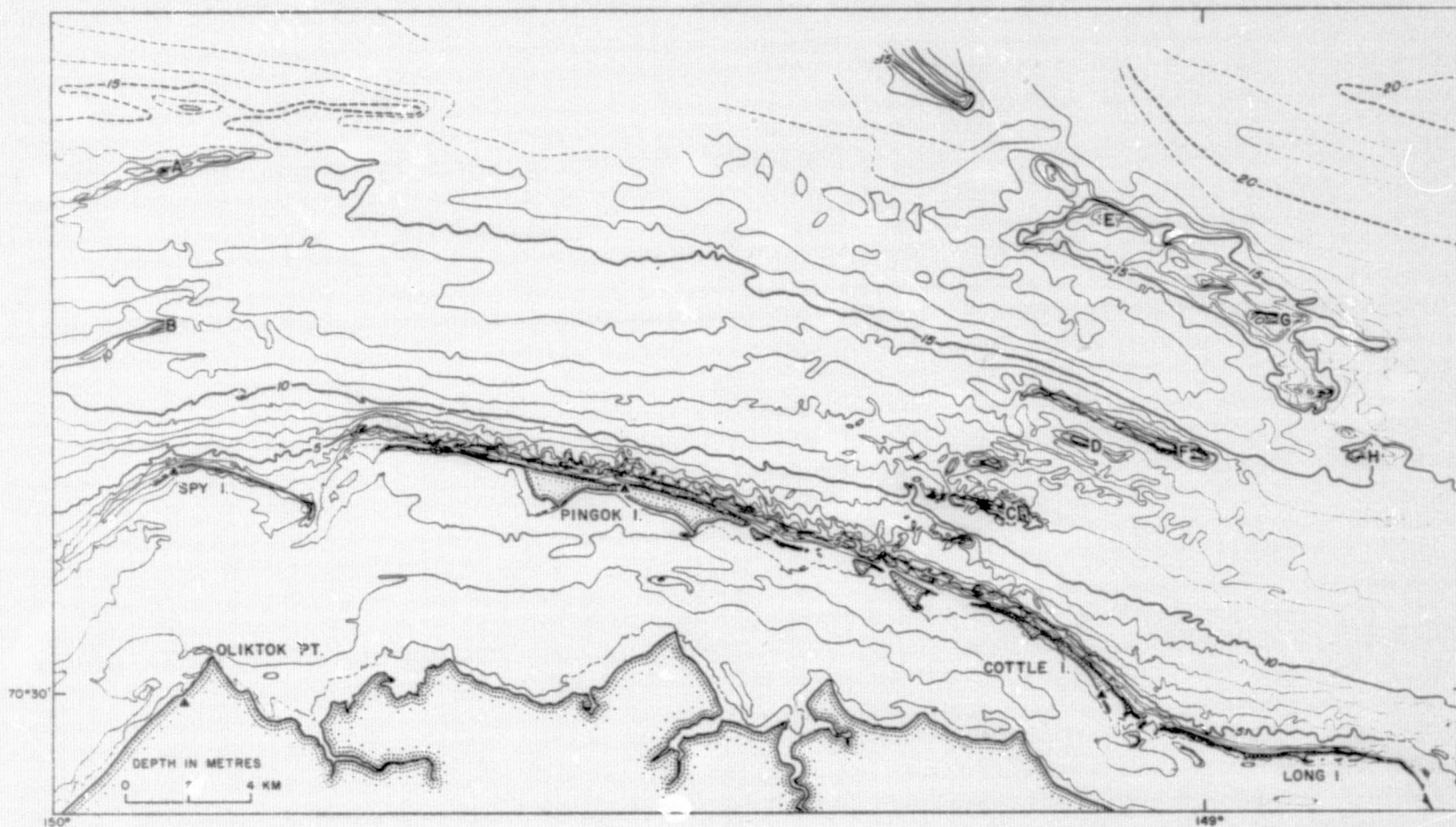


Figure 15. Bathymetry of inner shelf within central part of study area.

The contours are based on U.S. Coast and Geodetic Survey smooth sheets, surveyed 1949 through 1951 along a dense pattern of accurately controlled sounding lines. The location of individual shoal profiles shown in Figure 16 are keyed by letters.

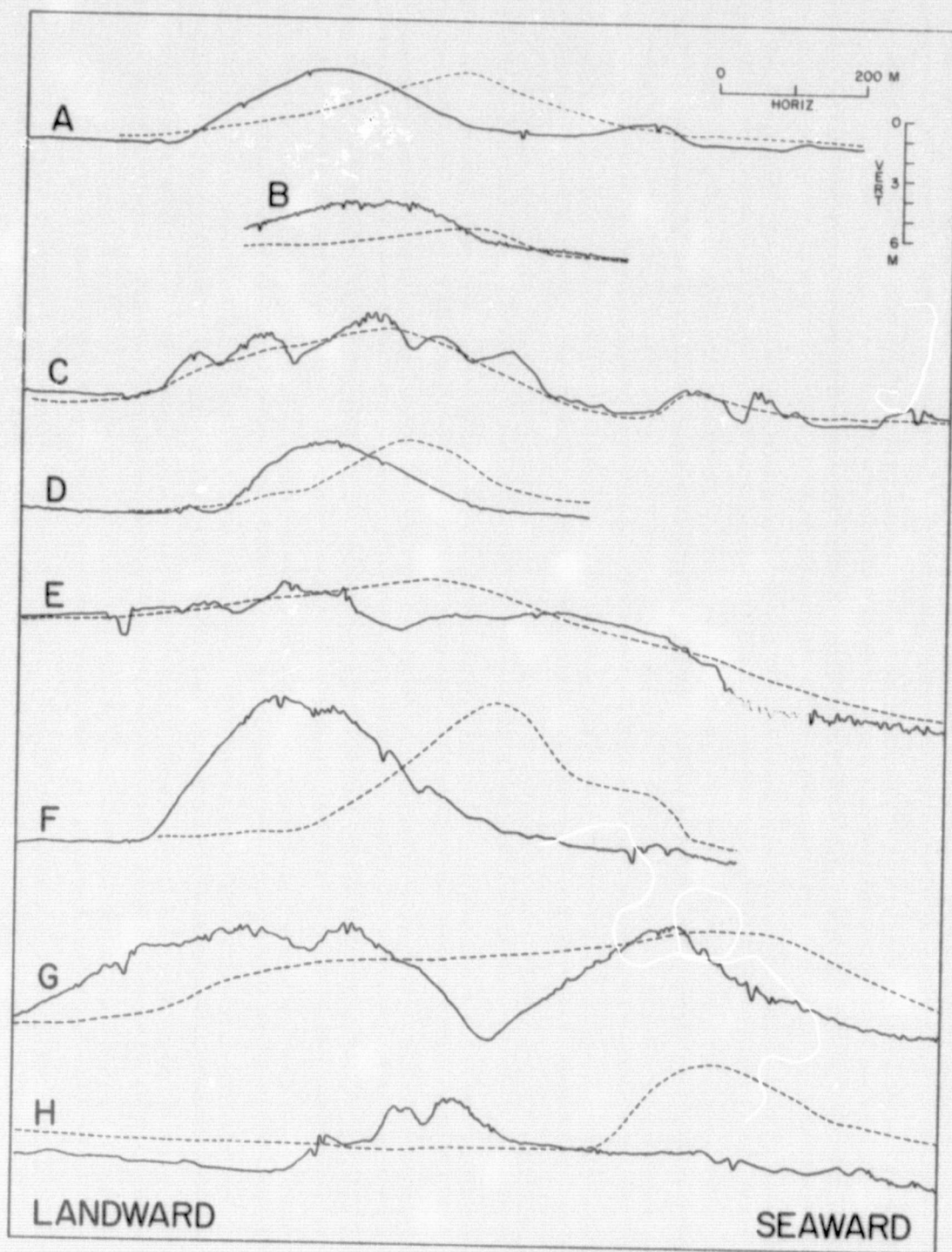


Figure 16. Cross-sectional profiles of shoals as surveyed 1949-51 (dashed line) and 1975 (solid line). All but one of the shoals have migrated landward through distances of 100 to 400 meters over 25 years.

average drawn through a number of data points on the contour chart, while the solid line was traced directly from the fathogram with all detail, the two profiles are remarkably similar. Ridge cross sections D through H, located farther offshore, show pronounced changes in profile and location. All have migrated landward 100 to 400 meters (avg. 200 m), and all but D have undergone considerable changes in shape. In general, the offshore ridges lying within the shear zone have changed more than those further inshore. The 1975 bathymetric data is unsuitable for evaluating any shore-parallel migration of shoals. Side-scan sonar records obtained in 1973 across the fast ice - pack ice boundary of the previous winter showed a change in ice gouge density in the vicinity of the boundary (Reimnitz and Barnes, 1974). The present detailed analysis of shear events on the shelf has enabled us to look more closely at how these relate to gouge density on the shelf.

Shear events on the shelf that were actually observed in Landsat images, or to which some broad time limits could be assigned, are shown in Figure 17. In the eastern part of the figure, where six sonar survey lines were run the following summer, ice gouge density patterns are shown by cross hatching. Figure 17 distinguishes between areas with 50 to 100 gouges and areas with more than 100 gouges per kilometer of ship's track. The highest gouge densities occur in an 8- to 14-km-wide zone seaward of the relatively undisturbed fast ice shown in Figures 1 and 17. The average gouge depths also are greater in this zone than on either side (Reimnitz and Barnes, 1974).

In several of our crossings of the undeformed fast-ice edge (early winter shearline) the change in gouge density was very abrupt and



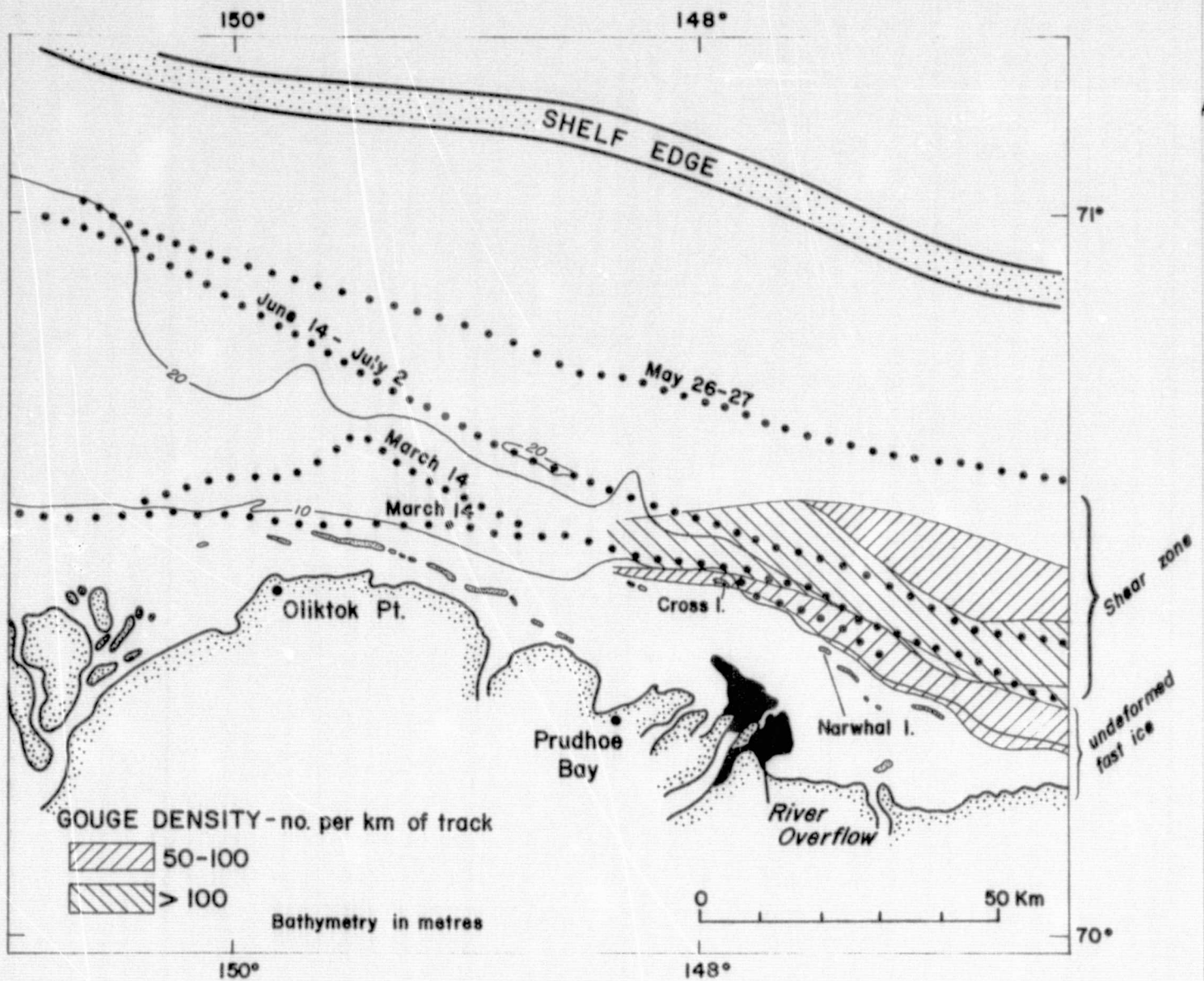


Figure 17. Locations of several major 1973 shear events (dotted lines) that were actually observed in Landsat images, or could be dated within narrow time limits. Related to these events are ice gouge density values (hachures) from 1973 sonographic surveys after Reimnitz and Barnes (1974). The dark area off the Sagavanirktok River defines the extent of freshwater overflow during the shear event of May 26-27.

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corresponded with this line to within the limits of resolution of Landsat imagery. The lower part of Figure 18 is a line drawing of ice gouges seen in sonographs along both sides of the ship's track (represented by the two parallel lines in the middle of the record) across the early winter shearline near Cross Island. In the fast-ice zone there are only a few minor gouges, but seaward the bottom is densely gouged.

The upper part of Figure 18 is a line drawing based on a high-resolution seismic reflection record obtained along exactly the same track as the sonograph below. It shows the highly irregular nature of internal reflectors within the area of abundant gouges, and rather evenly bedded materials in the area of smooth bottom.

Both the seismic record and the sonograph show a slight break in slope at the boundary between the two bottom morphologies. Landward of the break the seafloor is about 1-m shallower. The same phenomenon can be seen in several other crossings of the ice boundary, and we therefore do not consider this a mere coincidence. If indeed a causal relation exists between ice zonation and bottom morphology, the smooth high ground overlain by a thin unit of evenly bedded materials landward of the gouged area may be the result of (1) accretion from sediment-laden waters retained inshore of the first major grounded ice barrier, (2) faster sediment accretion due to lower rates of ice gouging and related resuspension and winnowing, or (3) current scour and redeposition along a grounded ridge system serving as a circulation boundary. Other possible explanations unrelated to the present ice zonation include the outcropping of more resistant older sediments or the presence of permafrost at the seafloor. While we feel that the

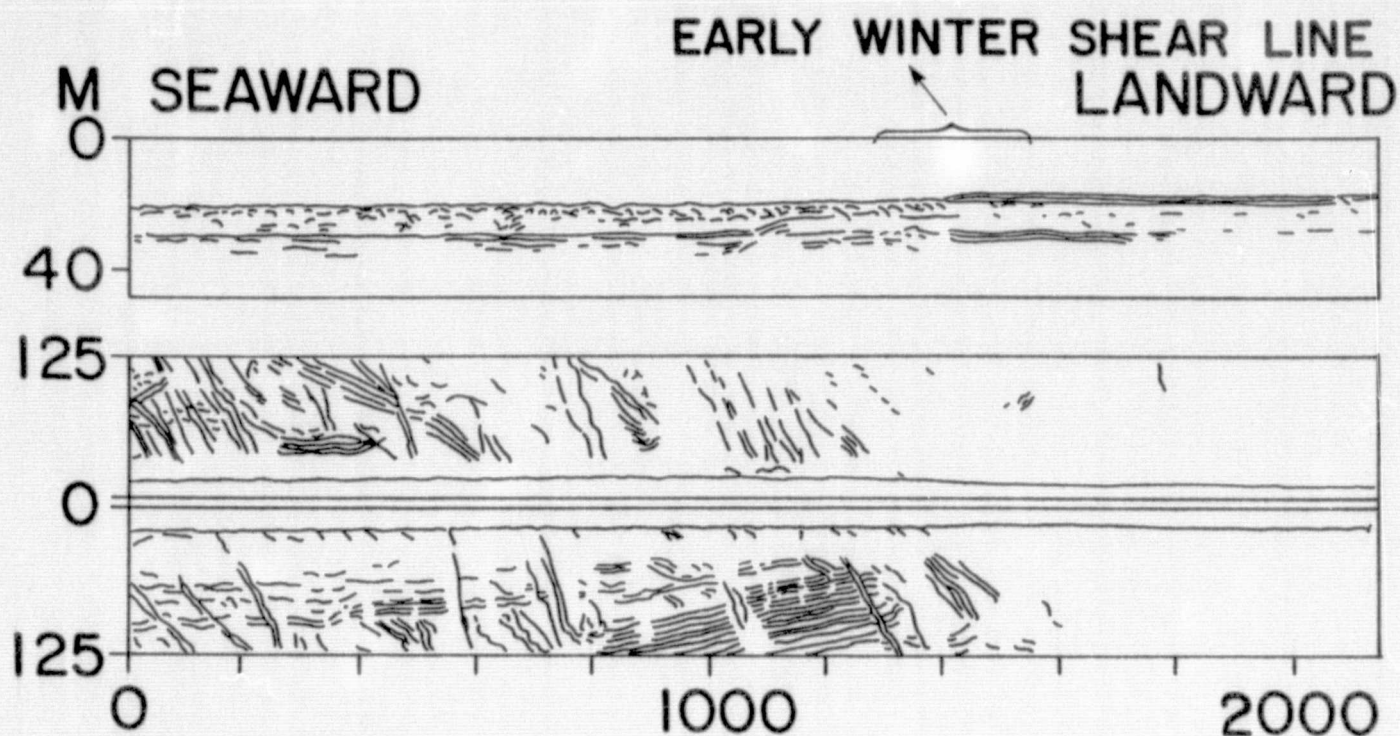


Figure 18. Line drawing of 1972 high-resolution seismic reflection (top) and ice gouges on side-scan sonar (bottom) records, obtained concurrently across early winter (1972) shearline boundary off Cross Island. Abrupt break in ice gouge density and nature of sub-bottom reflectors coincide with slight break in bottom slope. Landward of the shearline only minor gouges are apparent while seaward the bottom is densely gouged.

phenomenon observed is significant, and probably related to ice zonation, there are insufficient data to make an interpretation.

## DISCUSSION

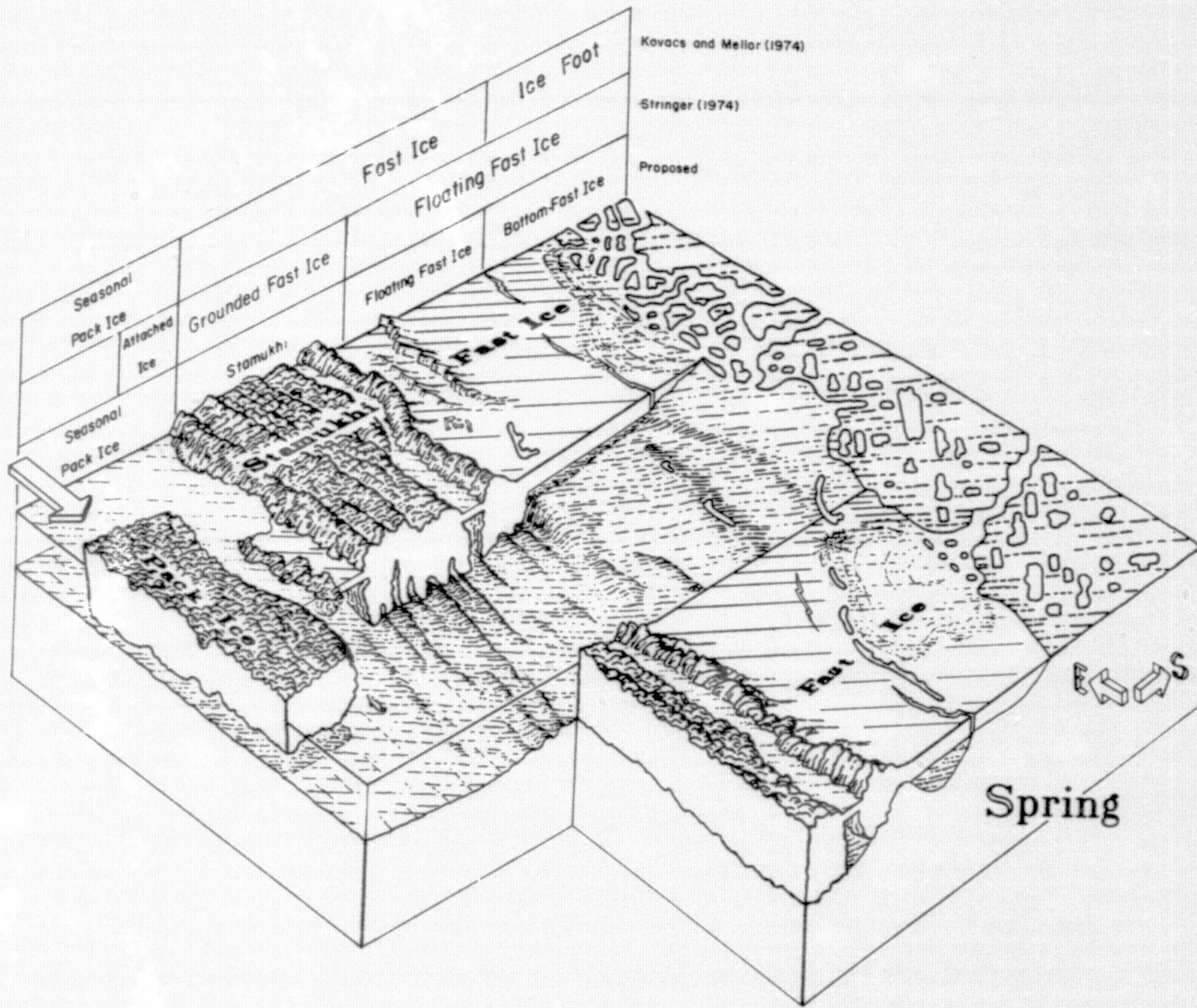
### *Ice Zonation and Terminology*

The results of this investigation indicate the presence of a distinct ice zonation on the Alaskan Beaufort Sea shelf, a pattern that usually recurs (annually) and is process-controlled. The data also suggests that previously used terms "fast ice zone" and "seasonal pack ice zone" are too broad and ill-defined, and require subdivision.

*Fast ice zone.* Using as the sole criterion that the ice be fast to shore or the seafloor for an unspecified period of time, and ignoring ice types and intermittent events, all ice on the shelf may qualify as fast ice, including the large early winter ridges of the shear zone, which are firmly grounded on the seafloor (Fig. 19). The zone in which these occur is very important in terms of ice morphology, dynamics, interaction with the shelf surface, and future commercial offshore development. This zone should be distinguished from the zone landward.

In this report we include within the fast ice zone those areas in which the sea ice has (a) essentially grown in place, (b) undergone relatively little deformation, (c) is truly fast after formation of the first major shore-parallel grounded shear or pressure ridge system (in water depth generally ranging from 10 to 20 m), and (d) only that ice which lies between land and the first major ridge system (Figs. 1 and 19). The fast ice zone does not include the system of grounded ridges along its seaward boundary, and in this respect we differ from the definition used by Stringer (1974) and Kovacs and Mellor (1974).





Kovacs and Mellor (1974)

Stringer (1974)

Proposed

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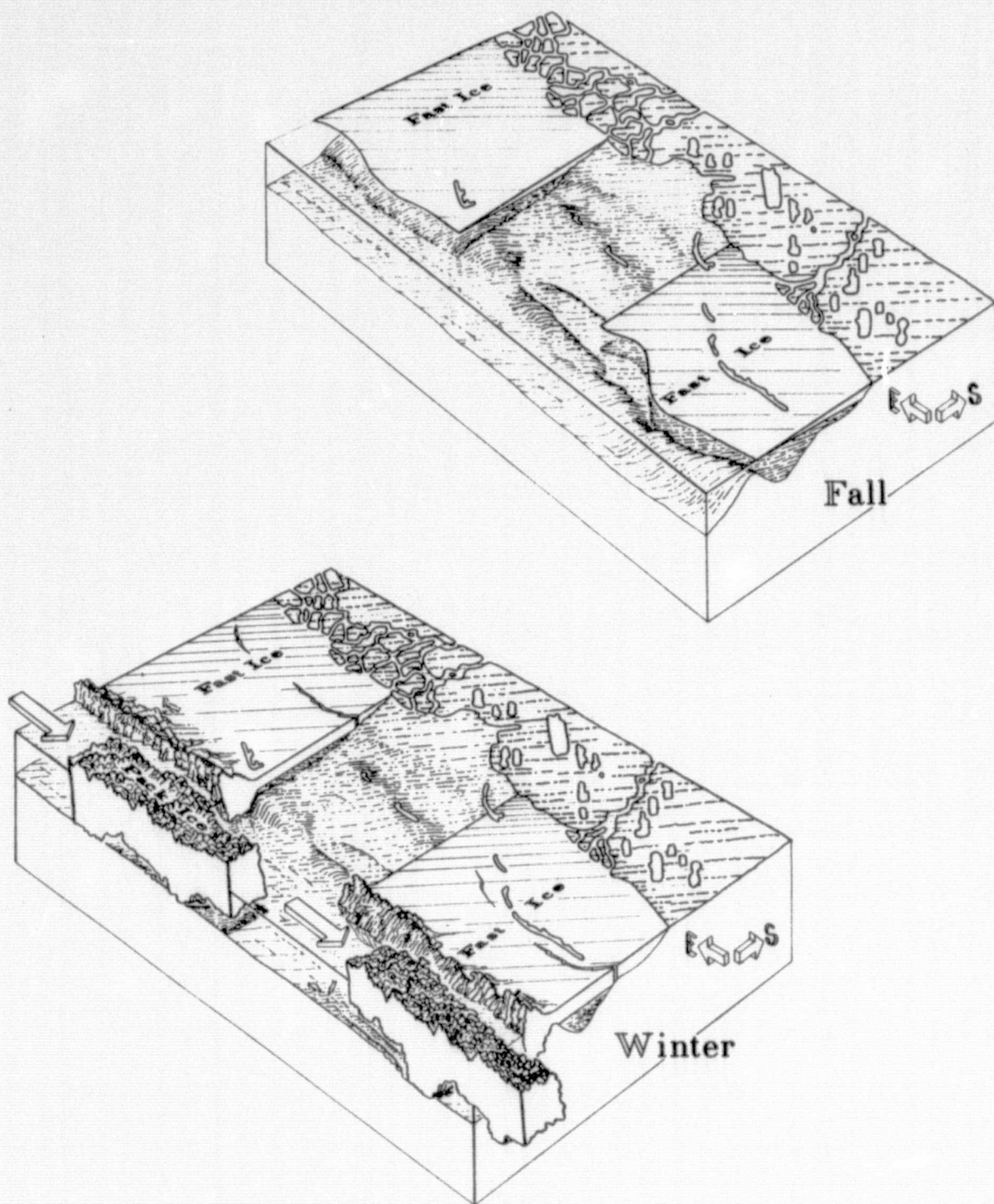


Figure 19. Seasonal development of ice zonation in relation to bottom morphology. Drawings by Tau Rho Alpha.

While it is the most meaningful one for the northern coast of Alaska, our definition may not be useful everywhere along the margin of the Arctic Ocean.

The fast ice zone as defined here is on the average 15 km wide between Point Barrow and Herschel Island (Fig. 1), with a minimum of less than 5 km at Herschel Island and a maximum of about 30 km west of the Colville Delta. In the eastern part of the area of Figure 1 the outer edge approximates the 20-m depth contour; in the western part it lies between the 10- and 15-m depth contours. Figures 8 and 10 show that seaward of the early winter shearline in Harrison Bay lies another broad zone of relatively undeformed ice extending seaward to the 20-m depth contour, up to 80 km from shore. Our observations of the ice breakup in 1973 and of ice gouge densities indicate that the major grounded ridges lie along the 20-m depth contour in this area. However, an increase in the gouge density along the early winter shearline inshore (10-m depth contour), indicates that some of the inshore ridges were also grounded. On the basis of its morphology and stability during late winter, this Harrison Bay ice between the 10- and 20-m depth isobath might have to be included under fast ice, or it may require still another term.

Ten to 75 percent of the fast ice zone along the coast of northern Alaska lies between the shore and the 2-m depth contour. Because by late winter the fast ice reaches a thickness of two meters, it rests on the bottom in most of these areas. In Harrison Bay this zone is up to 15 km wide (Fig. 1). The seaward boundary of the bottom-fast ice zone commonly is marked by tidal cracks (Figs. 13 and 19). Where the 2-m

contour is far from shore, the bottom from this point seaward drops off sharply (Reimnitz and Bruder, 1972), and the bottom sediments change abruptly from well-sorted sand inshore to poorly sorted mud offshore. These facts and various other observations (Barnes and Reimnitz, 1974; Reimnitz and Barnes, 1974) lead us to conclude that in terms of ice, bottom, hydraulic, and thermal processes the 2-m depth contour represents an important boundary. For these reasons we propose that the fast ice zone be further subdivided into floating fast ice and bottom-fast ice (Figs. 1 and 19), with the boundary at 2-m water depth. Kovacs and Mellor (1974, Fig. 3) use the term ice-foot for this part of the fast ice. This term, however, has generally been used for narrow belts of ice along beaches, rocky shores, or ice in contact with open water, formed by various processes of adfreezing on top or at the margin during onset of winter (for example, Zumberge and Wilson, 1953; Nichols, 1961; Owens and McCann, 1970; Gary, McAfee and Wolf, 1972; McCann and Carlisle, 1972; and Marsh et al., 1973). Ice-foot therefore should be distinguished from fast ice by its means of formation.

*Stamukhi zone.* Large grounded ridges form along the inner part of the shear zone seaward of the fast ice. The fast ice boundary is marked by the first major ice-deformational lineament (heading out from shore) seen in Landsat imagery. In the area of our detailed studies this shearline runs tangential to Cross Island. Westward the line swings landward and again closely approaches the next island chain some 60 km downdrift. From here it roughly follows the 10-m isobath in a broad landward curve across Harrison Bay and then seaward past Cape Halkett (Figs. 1 and 10).

Once formation of a grounded ridge stabilizes the fast ice, successive shear events generally occur further seaward. These events commonly are localized by offshore shoals (Figs. 10 and 19), where ridges interact with the sea floor. Grounded ice ridges forming on well-developed shoals in the area between Cross Island and Harrison Bay eventually stabilize the ice canopy to such distance from shore that the westward drift of pack ice within the Pacific Gyre is deflected offshore across Harrison Bay. This protects the bay and allows the formation of another extensive sheet of undeformed and immobile ice seaward of the early winter shear-line inshore. The edge of the drifting pack ice off Harrison Bay is then localized along the 20-m isobath, where ridges form in contact with shoals (Fig. 10).

There appears to be great similarities between the Alaskan Beaufort Sea and the Siberian Sea in the location of the fast ice edge near the 20-m isobath, and in its protection by grounded ice seaward. As pointed out earlier, stamukhi - grounded sea-ice features- occur for hundreds of kilometers along the 20-m isobath in the Siberian Arctic. Zubov (1945) states that (1) stamukhi often occur on shoals, (2) stamukhi initially are made up of piles of blocks of various dimensions and forms, (3) stamukhi usually last a few years, (4) stamukhi in the shallow regions of the Arctic Seas play the role of islands, protecting the shore from the pressure of ice, and (5) as a result the ice between the shore and the row of stamukhi that border the shore is not heaped but is flat and even. The term stamukha (singular for stamukhi) as defined in English-language glossaries does not convey the meaning implied by Zubov (1945). According to the Glossary of



Geology (Gory et al., 1972), a stamukha is "a fragment of sea ice stranded on a shoal or a shallows." Burke (1940) and Zubov (1945) include the grounding of floes as a mechanism that triggers the formation of stamukhi, but indicate that they also form by hummocking of thin ice over shoals.

The zone of grounded ridges that form seaward of the relatively undeformed fast ice off northern Alaska is a very important factor in the overall marine environment, and for future offshore development. It therefore seems appropriate to introduce a new term for this zone. Following the Russian use of the term stamukhi, we propose the term "stamukhi zone" for the recuring belt of grounded ridges and hummocks (Fig. 19).

In the area of our detailed studies the stamukhi zone is encompassed by the area of heavy black arrows in Figure 10. Off Cross Island the stamukhi zone is about 20 km wide and well defined. Off Harrison Bay it is over 50 km wide, but actually consists of two zones separated by a broad expanse of relatively undeformed ice. Previous studies of this area have assigned the ice of this zone to the fast ice zone (Stringer, 1974; Kovacs and Mellor, 1974). Considering ice dynamics, the stamukhi zone in early winter is a part of the shear zone (Kovacs and Mellow, 1974), where the pack ice of the Pacific Gyre rubs along the continent (Fig. 10).

#### *Pack Ice Drift*

Studying repetitive Landsat and NOAA-2 satellite imagery from the middle of March to the end of May 1973, we found that the pack ice in the Pacific Gyre moves westward along the continental shelf at 3 to 10



km/day. But much higher short-term drift velocities have been reported by others (Hibler et al., 1974; Hnatuk and Johnston, 1973). During the period covered by our imagery, slippage between the Pacific Gyre and stationary ice along the coast generally occurred at the shelf edge. Ice on the continental shelf remained stationary within the spatial resolution of Landsat imagery (300 m) for up to 20 days and probably longer. Slippage occurred intermittently within or along the seaward edge of the stamukhi zone on the continental shelf, where much of the available energy is expended on the sea floor.

Regardless of where the slippage occurs, we found individual events to be restricted to a zone several hundred meters wide and not distributed over a 50-km-wide zone as stated by Crowder et al. (1973) and Hibler et al. (1974). Thus, the calculated ice movement vectors did not indicate drag effects near the edge of the stationary ice as postulated by Kovacs and Mellor (1974). In fact, the rate of movement in several instances was higher at the shearline than it was ten or more kilometers seaward.

#### *Factors Controlling Location of Fast Ice Edge*

Because the edge of the fast ice and the stamukhi zone forms year after year at roughly the same locations in the Arctic, it is of interest to examine the causes that localize the formation of major grounded ridges and hummocks in our study area.

Croasdale (1974, p. 298) has pointed out that the fast ice boundary, being similar from year to year regardless of the presence of multi-year floes, implies that grounded ridges along the fast ice edge must be first-year ridges. He also mentions the further implication that newly formed

ridges may therefore seldom have keels deeper than 18 m, the presumed water depth at the fast ice edge. Indeed, submarine sonar data indicates that only 1 percent of all ridge keels are deeper than 18 m (Hibler, 1974, p. 299), a depth that may be related to the mechanisms and structure of pressure ridges (Parmenter and Coon, 1973). Hibler (1974, p. 300) believes that more important than the distribution of keel depths may be the increased current drag on ridge keels, where the boundary layer under a moving ice cover impinges on the bottom in shallow water. The fast ice generally grows from the shore outward in response to the faster cooling rate of shallow water, and the lower salinity inshore. Is there some factor of fast ice thickness or strength at a particular time of the season that determines at what distance from shore the forces of the pack ice are arrested? In some areas of the Arctic the extent of fast ice is determined by the configuration of land masses, providing shelter against the forces of the drifting pack. All of the above factors were considered in our attempt to answer what controls the location of the fast ice edge in our study area.

Conditions in the winter of 1972-73 were ideal for determining what ice types are involved in the stamukhi zone protecting the fast ice edge. There was no multi-year ice on the shelf from freezeup until mid-winter and therefore the ridges of the stamukhi zone were formed from first-year ice. Our study of ice morphology and behavior indicates that the stamukhi zone straddles the 10- to 30-m depth range. Ice gouge density patterns off Harrison Bay, surveyed in 1972, imply that the stamukhi zone extends to at least 40 m depth. Thus, the 18-m ridge-keel depth limit reported for 99 percent of free-floating ridges

seems to have no special significance for shallow water depth. If, on the other hand, increased current drag on ice keels in shallow water were effective in stabilizing the edge of pack ice drift on the shelf, this should also result in the formation of hydraulic bedforms. Side-scan sonar techniques used in our studies are well suited for the detection of hydraulic bedforms, we have not noticed anomalous increases of current-produced bottom features in the stamukhi zone. Therefore, current drag probably is not an important factor in controlling the location of the fast ice edge and the stamukhi zone.

Evaluating how the strength of the fast ice influences the location of the stamukhi zone is difficult without adequate seasonal data. The fast ice growth rate and strength should be influenced by variations in surface water salinity and temperatures on the shelf. These parameters were plotted for August and September 1972 in the study area (Hufford et al., 1974). The configuration of the fast ice edge during the following winter does not show irregularities that can be attributed to changes in water characteristics along the coast. Also, the greater width of fast ice in Harrison Bay, where post-summer water cooling rates in extensive shallow areas should be higher than elsewhere, apparently is best explained in terms of ice dynamics, as outlined earlier. For these reasons we feel that the fast ice itself is not a primary factor in determining where shearing events and ridge formation occurs on the shelf.

The last factor to consider is the relation of coastal configuration to pack ice drift, and how this may influence the location of the fast ice edge and stamukhi zone. The regional setting is that of an irregular

coastline tangential to the arctic pack-ice drift within the Pacific Gyre. Hibler et al. (1974) thought of this gyre as "a large cohesive wheel slipping at the edge." In this model, the location of the wheel's (gyre's) rim is determined by the bumps in the road surface - the coastal promontories.

Major promontories in the area are Herschel Island, Barter Island, Cross Island, Cape Halkett, and Point Barrow (Fig. 1).

At the first three promontories our observations are consistent with the assumed model. The fast ice zone is narrow, and ridge systems seaward are closely spaced and parallel, describing the trajectories along which the wheel slips (Figs. 8 and 10). Downdrift from the promontories the early winter slip surfaces tend to swing landward, following the broad indentations in the coastline. Later in the season the slip surfaces generally lie farther seaward, along rather straight lines extending from one promontory to the next. In keeping with the assumed model, the widely spaced slip surfaces in the regions between promontories can be related to changes in rotation rate of the slipping wheel. When it slows down, the pressure of the pack is applied between the promontories on the fast ice in early winter, or on the strongly resistant stamukhi zone later in winter.

The configuration of the fast ice zone in the vicinity of Cape Halkett needs further explanation in terms of our assumed model. The early winter shearline and ice ridges describe a broad landward curve across the 90-km wide Harrison Bay (Figs. 8 and 10), roughly following the 10-m depth contour. Ice slipping westward along this line piles up toward Cape Halkett and is deflected seaward for some distance

north of the cape. Later in the season, shear events projecting straight across the bay interact with the early ridge systems at an angle. The interaction of early winter ridges with late winter ice drift north of Cape Halkett results in the formation of major but highly irregular ridge and hummock patterns (Fig. 10). Parts of these apparently are grounded, and provide shelter for the growth of another extensive sheet of undeformed ice seaward of the early winter shearline in Harrison Bay.

The data analyzed suggest that the configuration and location of the recurring stamukhi zone and extent of the fast ice in the study area may be best explained in terms of a model in which the westward pack ice drift interacts with an irregular coastline and offshore shoals.

#### *Effects of Ice Zonation on Marine Geology and Bottom Processes.*

For the greater part of the year the relatively undeformed fast ice rests quietly against the shoreface, unaffected by the forces of the marine environment. Pronounced deformation of beach deposits by sea ice during the winter time is largely restricted to the major promontories such as Cross Island. Even during the short summers, the grounded ridges of the stamukhi zone commonly shelter the inner shelf and shore from drifting ice and limit the fetch for wave generation.

The stamukhi zone, straddling the mid-shelf region, is where much of the available marine energy is expended on the shelf surface on a year-round basis. Ridging initially occurs between the 10- and 20-m isobaths, stabilizing the fast-ice edge. Ridge accretion against the

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initial ridge system and stabilization by bottom contact gradually shifts the dynamically active zone seaward (Fig. 19). The end result is a wide stamukhi zone. The high amount of energy expended on the seafloor during this process and the eventual dislodging of grounded ice in the succeeding summers is manifested in the high ice gouge intensities in this zone and the chaotic nature of internal sedimentary structures. Also, a sediment textural boundary (Barnes and Reimnitz, 1974) roughly corresponds with the fast ice edge as delineated in Figure 1, suggesting a possible relation between ice zonation and sediment transport.

There is a striking relation between ice ridge lineation in the stamukhi zone and bathymetric shoals (Fig. 10). This suggests that ice deformational events may be affected by ice interaction with these shoals. A similar relation has been inferred for regions along the Siberian coast, where recurrent stamukhi form on offshore shoals (Zubov, 1945). Offshore shoals between Harrison Bay and Cross Island have been studied with seismic profiling techniques. The Holocene marine sediments in this region generally are only several meters thick on a flat-lying sub-bottom reflector. The shoals correspond to a thickening marine section, indicating that they are constructional features postdating the last marine transgression. The shoals and the modern barrier island have rather similar cross sections. However, the shoals are composed of well-sorted sand with some individual pebbles (Reimnitz and Barnes, 1974), while the barrier islands consist of sandy gravel to gravelly sand. Because of this difference in composition the shoals do not appear to represent drowned barrier islands. Nearshore



bars 1 to 3 m high are present along Pingok and adjacent islands. These are migrating under the influence of summer waves and currents (Short, 1975). The much larger shoals under discussion clearly do not form or migrate under the influence of similar nearshore processes.

All available evidence leads to the conclusion that the shoals are not hydraulic bedforms related to open-water conditions, but were formed and presently are migrating under the influence of ice-related processes. Future studies will have to show whether such shoals form by (a) the bulldozing action of ice during one or several major events, (b) the cumulative effects of several thousand years of ice push by grounded ridges along the edge of the Pacific Gyre rubbing against the continent, (c) winter currents being channeled along major grounded ridge systems to concentrate available sediments into sand ridges, or whether (d) several of these processes act together to form the shoals.

Shoals in the stamukhi zone are not restricted to the region of our studies but extend westward to Point Barrow, according to National Ocean Survey chart No. N.O. 16004 (1973 edition). East of Cross Island similar shoals are shown, but they are not as numerous as in the western sector. This may be due to a lack of sounding data.

Where the stamukhi zone lies close to coastal promontories, as off Cross Island, the seafloor slopes steeply away from the beach, whereas bottom slopes are gentle in other areas where the stamukhi zone lies several kilometers offshore.

In summary then, we see a causal relation between the overall shelf

profile and winter ice dynamics and ice zonation. On low-latitude shelves the high-energy surf zone shapes the shelf profile in the coastal environment. Along the Beaufort Sea coast, ice dynamics in the stamukhi zone of the central shelf leave an imprint in the form of pronounced shelf profile anomalies. But the effects of the stamukhi zone are probably not restricted to marine geology, geomorphology, and seafloor dynamics.

If major ice ridge systems conform to the bottom for considerable distances, the stamukhi zone may be an oceanographic barrier separating the inner shelf from the open ocean. The reported sediment boundary along the fast ice edge may be related to this in some still unknown way.

Winter temperature profiles of floating ridges with values as low as  $-24^{\circ}\text{C}$  in the upper part, increasing to seawater temperature at the keel, have been reported. Elimination of water circulation by bottom contact would result in lower keel temperatures of a grounded ridge, and such lowered temperatures would ultimately reach the sea floor. Thus, the thermal effects of grounded ridges in the stamukhi zone may affect the nature and distribution of offshore permafrost.

#### *Implications for Offshore development*

Several aspects of results reported here are of relevance to planned offshore development of the Prudhoe Bay oil field. In the near future offshore development probably will be restricted to the shelf landward of the stamukhi zone, the least hostile environment. Such developments may include construction of artificial islands, as in

the MacKenzie Delta region, and special drilling platforms to withstand the forces of drifting ice floes and ice island fragments.

The extent of the fast ice zone off Prudhoe Bay is controlled by Cross Island, which appears to be a typical barrier island. This island has changed little since it was mapped accurately some 25 years ago. A small house on this island has been unaffected by ice push for some 30 to 40 years. The shoals between Cross Island and Harrison Bay, whatever their origin, today take the brunt of the ice forces year round. Moreover, they seem to influence winter ice dynamics and extent of the fast ice. The shoals have migrated several hundred meters during a 25-year period, yet they have retained their overall identity.

From these observations it appears that artificial drilling islands, placed within the fast ice zone shoreward of the stamukhi zone, have a good chance of withstanding the forces of the ice in this area. Furthermore, similar structures properly placed in the stamukhi zone might be used to extend the area of fast ice seaward.

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## SUMMARY OF CONCLUSIONS

- (1) The ice pack rotating clockwise within the Pacific Gyre rubs along the continental margin north of Alaska, resulting in the formation of major linear ridge systems every winter. Initially, their location is principally controlled by major promontories. These ridges are stabilized by grounding, which is focused by shoals downdrift of major promontories.
- (2) Slippage occurs intermittently along or seaward of the grounded ridges, forming new grounded ridges in a widening zone, the "stamukhi zone", at depths of 10 to 40 m.
- (3) During long periods between these intermittent events along the stamukhi zone, pack ice drift and slippage is continuous along the shelf edge at average rates of 3 to 10 km/day.
- (4) Slippage is observed to occur in a zone several hundred meters wide, the ice for tens of kilometers seaward of the slip boundary moving at uniform rates, generally with no observed drag effects.
- (5) The seasonal fast ice grows in the protected belt between the stamukhi zone and the land, remaining relatively undeformed.
- (6) This fast ice zone is further subdivided into floating and bottom-fast ice. The latter may extend up to 15 km from land, and can compose as much as 75 percent of the total fast ice zone.
- (7) This zonation is different from previously used zonations, in that the stamukhi zone is not part of the fast ice zone. The proposed nomenclature emphasizes ice interaction with the shelf surface.
- (8) Much of the available marine energy is expended on the seafloor within the stamukhi zone, while the inner shelf and coast are relatively protected year round.

- (9) Energy expended on the seafloor is manifested in the high ice gouge density, deep ice gouges, and intensely disrupted internal sedimentary structures within the stamukhi zone. There also is strong evidence that the stamukhi zone influences distribution of sediment textures on the shelf.
- (10) Shoals that presently localize major linear shear ridge elements within the stamukhi zone may originally have formed in response to ice-bottom interaction within the shear zone and today appear to be migrating under the influence of ice-bottom interaction.
- (11) Anomalies in the arctic shelf profile are related to sea ice zonation and sea ice dynamics.
- (12) Artificial islands similar in nature and location to the shoals studied should be able to withstand the forces of the ice for 10 to 20 years.
- (13) It seems possible that artificial islands, properly placed, may be used to modify the location of the shear zone and open larger areas of the shelf to development.



#### ACKNOWLEDGMENTS

We are grateful to Arctic Marine Freighters for their continuing assistance to our small boat operations staged out of Prudhoe Bay. The study of Landsat-1 imagery was funded by NASA (contract no. S-7024-AG). Harry Hill of the U.S. Geological Survey has operated and maintained the electronics equipment aboard our vessels, and deserves special thanks.

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## FIGURE CAPTIONS

- Figure 1. Study area showing bathymetry and place names. The extent of relatively undeformed fast ice was largely determined from Landsat-1 images between March 8 and April 21, 1973. Extent of 2-m-thick bottom-fast ice has been traced from bathymetric contours.
- Figure 2. October 4th, 1972 Landsat-1 image showing formation of new ice on the shallow inner shelf, and drift accumulation against south side of barrier islands. No old ice is visible within the 100 x 100 nautical miles covered by the image (1073-21223).
- Figure 3. March 14 through 16, 1973 Landsat images (nos. 1234-21175, 1235-21241, 1236-21297) show a recent shore-parallel lead (A) and roughly shore-normal lead (B). The configuration of (A) indicates that the ice seaward has been displaced eastward by 2 km relative to the stationary ice. In early April (Landsat image nos. 1252-21175, 1253-21233, 1254-21292), an active shearline (C) paralleling the shelf edge was associated with westward pack ice displacements of 4 km/day. The displacement, shown by length of arrows, was uniform through a 24-km-wide zone seaward of the slip face.
- Figure 4. Visible-band NOAA-2 satellite image taken April 5, 1973. The large (40 x 15 km) polynya shown in Figure 3(D) can be identified on this image. A curvilinear lead extends from the shelf-parallel shearline for hundreds of kilometers into the Arctic Ocean.

Figure 5. Comparison of the location of major lead seen on NOAA-2 imagery March 26, March 31, and April 1, 1973. The large dots mark points along the lead identifiable in all three images. The pack ice in a 350-km-wide zone north of the coast-parallel shearline moved uniformly at about 10 km/day.

Figure 6. May 27, 1973, Landsat image (no. 1308-21290) showing recent irregular refrozen cracks about 10 km west of Cross Island produced by ice deformation along early winter shearline. A pronounced coast-parallel, active shearline bulges seaward along the 20-m isobath across Harrison Bay. Comparison with ice features identifiable on previous days image reveals uniform displacement of 6 km/day over the shown strain network extending some 90 km seaward of the shearline. No drag effects near the stationary ice/drifting pack ice boundary are visible.

Figure 7. Tracing from NOAA-2 visible-band images of April 5 and May 27, 1973, showing westward displacement of long lead seen in Figures 4 and 5. During the 52-day period displacements ranged from 160 km (3 km/day) near the continent to 80 km (1.5 km/day) at a point 450 km seaward of the coast. Differences in displacements are considered representative of points at various distances from the center of the clockwise rotation within the Pacific Gyre.

Figure 8. July 2, 1973 Landsat-1 image (1344-21283) showing initiation of sea ice breakup. Ice on inner and outer shelf west of Oliktok Point is breaking up and moving westward. A 15-km-wide zone coinciding with zone of major shear events during

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Figure 8. cont'd

winter remains intact. This breakup pattern suggests the presence of stamukhi along the 20-m isobath.

Figure 9. Mosaic of U-2 color infrared photos taken from an altitude of 20,000 m on July 21, 1974. Flightline extends north from Prudhoe Bay. Sea ice morphology is similar to that of 1973. Smooth fast ice, lightly deformed shortly after freezeup, extends to just beyond Reindeer Island, followed by strongly lineated and rough ice in the stamukhi zone and a zone of mobile ice on the outer shelf.

Figure 10. Generalized model of ice drift within area of detailed study, showing predominant movement of pack ice along well-defined shearlines, dominant wind direction, and location of charted shoals (hachured areas). Note striking correlation between distribution of shoals and major ice lineations traced from Landsat images, which represent shear ridges, pressure ridges, and linear hummock fields.

Figure 11. Oblique aerial photograph taken northeast of Pt. Barrow on August 13, 1975. Grounded ridges (stamukhi) occur along lines paralleling isobaths (upper fourth of photo), marking a distinct boundary between scattered ice on inner shelf (central part of photo) and tightly packed ice beyond.

Figure 12. June 1970 photograph of ice push features on Narwhal Island. Such ice push features and associated beach deformation recur annually on major coastal promontories such as Narwhal Island and Cross Island that are exposed to shearzone ice dynamics.

Figure 13. Example of barrier island beaches that lie downdrift of major promontories and landward of shoals. Photographed May 1972 on Long Island. The 2-m isobath seaward of beach is marked by characteristic tidal crack in relatively smooth fast ice.

Figure 14. Comparison of bottom profiles off Cross Island, where the shear zone impinges on the coast, and Spy Island, (Fig. 15), protected by stamukhi on offshore shoals.

Figure 15. Bathymetry of inner shelf within central part of study area. The contours are based on U.S. Coast and Geodetic Survey smooth sheets, surveyed 1949 through 1951 along a dense pattern of accurately controlled sounding lines. The location of individual shoal profiles shown in Figure 16 are keyed by letters.

Figure 16. Cross-sectional profiles of shoals as surveyed 1949-51 (dashed line) and 1975 (solid line). All but one of the shoals have migrated landward through distances of 100 to 400 meters over 25 years.

Figure 17. Locations of several major 1973 shear events (dotted lines) that were actually observed in Landsat images, or could be dated within narrow time limits. Related to these events are ice gouge density values (hachures) from 1973 sonographic surveys after Reimnitz and Barnes (1974). The dark area off the Sagavanirktok River defines the extent of freshwater overflow during the shear event of May 26-27.



Figure 18. Line drawing of 1973 high-resolution seismic reflection

(top) and ice gouges on side-scan sonar (bottom) records, obtained concurrently across early winter (1972) shearline boundary off Cross Island. Abrupt break in ice gouge density and nature of sub-bottom reflectors coincide with slight break in bottom slope. Landward of the shearline only minor gouges are apparent while seaward the bottom is densely gouged.

Figure 19. Seasonal development of ice zonation in relation to bottom morphology. Drawings by Tau Rho Alpha.

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DISTRIBUTION AND CHARACTER OF NALEDs IN  
NORTHEASTERN ALASKA

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# Abstract

An examination of the distribution of river naleds seen in Landsat satellite imagery and high- and low-altitude aerial photography of Alaska's North Slope indicates that these features are widespread east of the Colville River and less abundant to the west. Where naleds occur, stream channels are wide and often form braided channels. Their distribution can be related to changes in stream gradient and to the occurrence of springs. Large naleds, such as on the Kongakut River, often remain through the summer melt season to form the nucleus of icing in the succeeding winter. Major naleds also are likely to significantly influence the nature of permafrost in their immediate vicinity. The map of naleds may serve as a guide to the occurrence of year-round flowing water, a sparse commodity in northern Alaska.

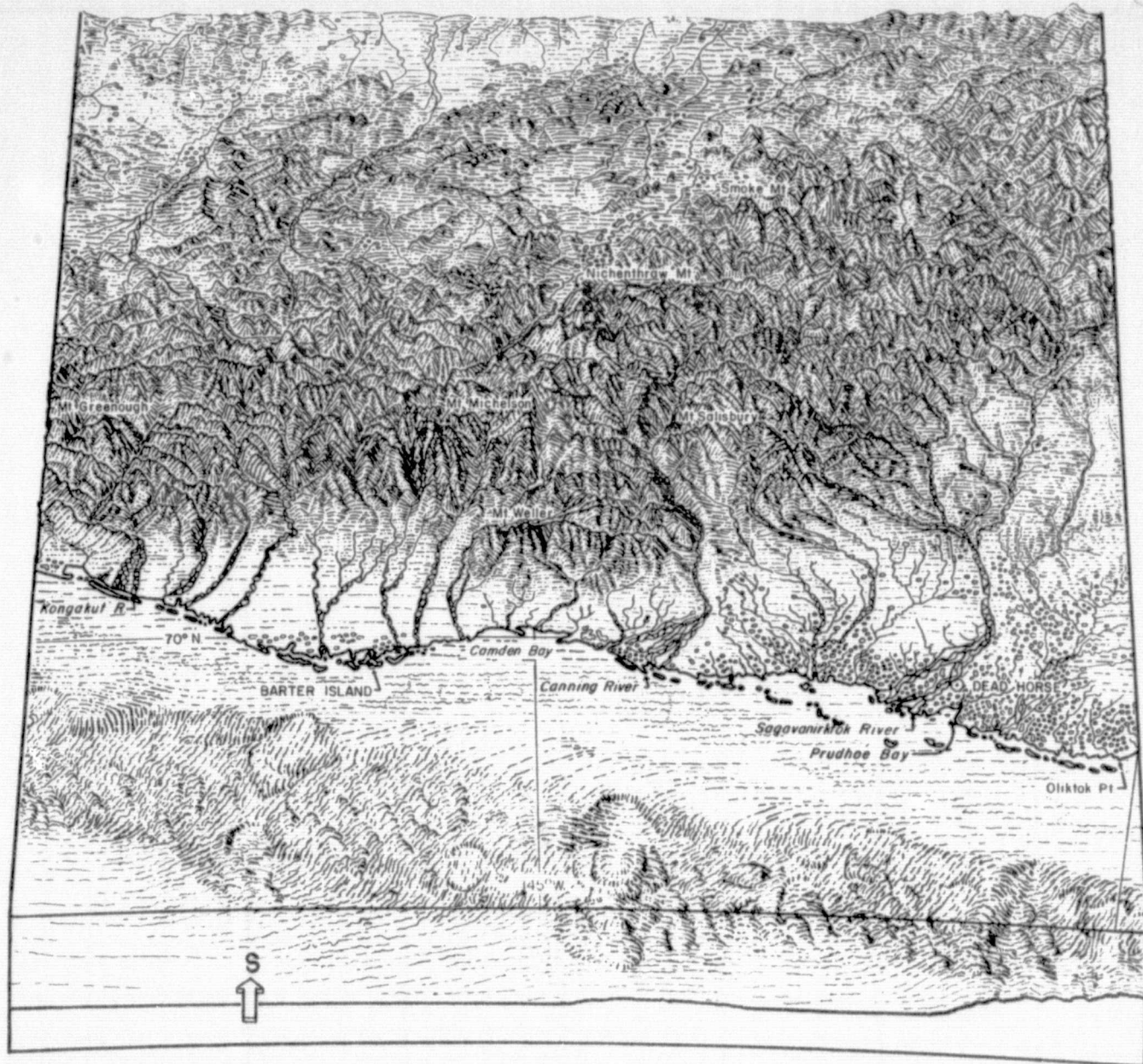
## Introduction

Repetitive Landsat-1 imagery can be used for seasonal observations of naleds on a regional scale. Although the existence of naleds on the North Slope of Alaska (Fig. 1) has been known for some time (Leffingwell, 1919), regional mapping and seasonal monitoring have not been attempted. Here, we present a study of the distribution, longevity, and character of arctic river naleds and speculate on their causes and effects, and also their importance to human development in the region.

Icing refers to the process of progressive ice growth or accretion on a frozen surface. It is an imprecise term, in that it is also used to designate many other phenomena of the Arctic. In reference to arctic rivers, it has been used to designate both the processes of ice buildup and the actual body of ice thus formed (Carey, 1973). Equivalent terms are the Russian "naled" and the German "aufeis", both of which refer to the physical feature formed. We suggest that "icing" be used for the process and "naled" for the feature formed. Thus, naleds are formed by icing.

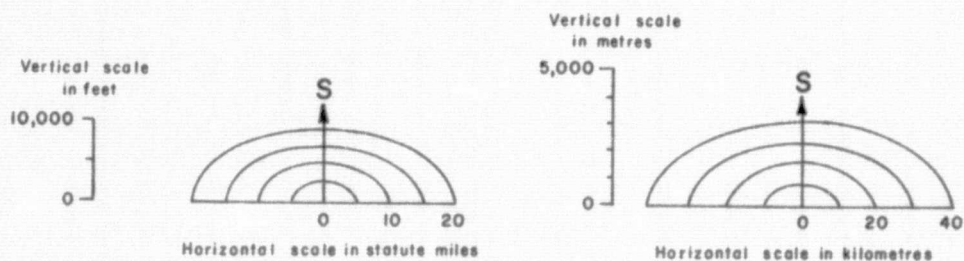
The type of icing with which we are concerned occurs when water repeatedly or continuously emerges onto the land or ice surface during the winter periods of subfreezing temperatures and freezes in successive layers. This water may seep from the ground, from a river, or from a spring (Carey, 1973; Anisimova et al., 1973; Hopkins et al., 1955). Thus, naleds may be classified genetically as ground-, river-, or spring-naleds, although most result from a combination of these factors.

Russian studies (Anisimova et al., 1973) have shown that in some river basins in northeastern Siberia naleds accumulate up to 25-30% of the annual



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VERTICAL EXAGGERATION 7:1



SCALE

Physiography by Tau Rho Alpha

## Coast and Shelf of Northeastern Alaska

Figure 1. Physiographic diagram of study area. Diagram by Tau Rho Alpha.

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volume of river flow and up to 60-80% of the subsurface drainage. Naleds commonly form year after year in the same locations, generally with the same shape and size. River flood plains commonly are widened as spring floodwaters are forced to flow around naled mounds. The same studies also indicate that the size and location of naleds are a function of (1) discharge source (stream, groundwater, or spring), (2) hydrostatic head, and (3) geologic setting.

Naleds that appear to persist and continue to grow throughout the winter indicate usable fresh water sources (Hopkins et al., 1955). Considering the present rapid development of the arctic region and the scarcity of fresh water, knowledge of the distribution and character of naleds could have important implications. In addition, construction projects such as roads are affected by both naturally occurring naleds and those induced by development activities (Anderson et al., 1973). Potentially, any alteration of a balanced hydrologic-permafrost-geologic regime may induce icing conditions and cause naleds to form. In areas where naleds extend to the coast, as in the Icy Reef area (Fig. 4), they have definite influence on the deltaic and coastal-marine processes.

#### Background Information

The North Slope of Alaska falls into three major physiographic provinces (Wahrhaftig, 1965; Figs. 1 and 2): (1) the Arctic Coastal Plain, (2) the Arctic Foothills Province, and (3) the Brooks Range. The coastal plain is a broad, flat tundra surface with numerous lakes that includes the deltas and streams draining the higher terrain to the south. West of the Colville River the streams are meandering, while to the east braiding is more common. The Foothills Province is characterized by rolling terrain with some bluffs

along the river courses. Most of the known springs occur in this province, where abrupt decreases in river gradients occur. Both the Arctic Coastal Plain and the Foothills Province narrow toward the east, where the Brooks Range approaches the coast near the Canadian boundary. The Brooks Range is the source for all of the major north-flowing rivers.

The seasonal freeze-thaw cycle controls the development and dissipation of river ice in northern Alaska. All of the rivers of the North Slope flow in the zone of continuous permafrost (Walker, 1974). River ice forms during mid to late September, after mean temperatures are below  $0^{\circ}\text{C}$ . By the end of December when temperatures are often below  $-20^{\circ}\text{C}$ , river ice is commonly more than 1 metre thick. Ice continues to thicken to a maximum of about 2 metres until May, when temperatures rise above freezing and the melt season begins. During late May and early June, thawing proceeds rapidly, flow begins on top of river and sea ice, and eventually most of the river ice breaks up and flows downstream (Walker, 1974). During summer, temperatures are above freezing and streamflow is unimpeded by ice.

Two conditions must be met before icing occurs and a naled forms. First, there must be a source of flowing water beneath a surface whose temperature is below  $0^{\circ}\text{C}$ . Second, there must be a barrier to the flow of water that forces it to the surface. These barriers are commonly provided by the total freezing of the river cross section, ground freezing, or reduction in aquifer permeability owing to permafrost or outcrops of impermeable strata (Sokolov, 1973; Carey, 1973).

River naleds develop after the formation of the seasonal ice cover (Carey, 1973). If water remains unfrozen below the ice cover in the

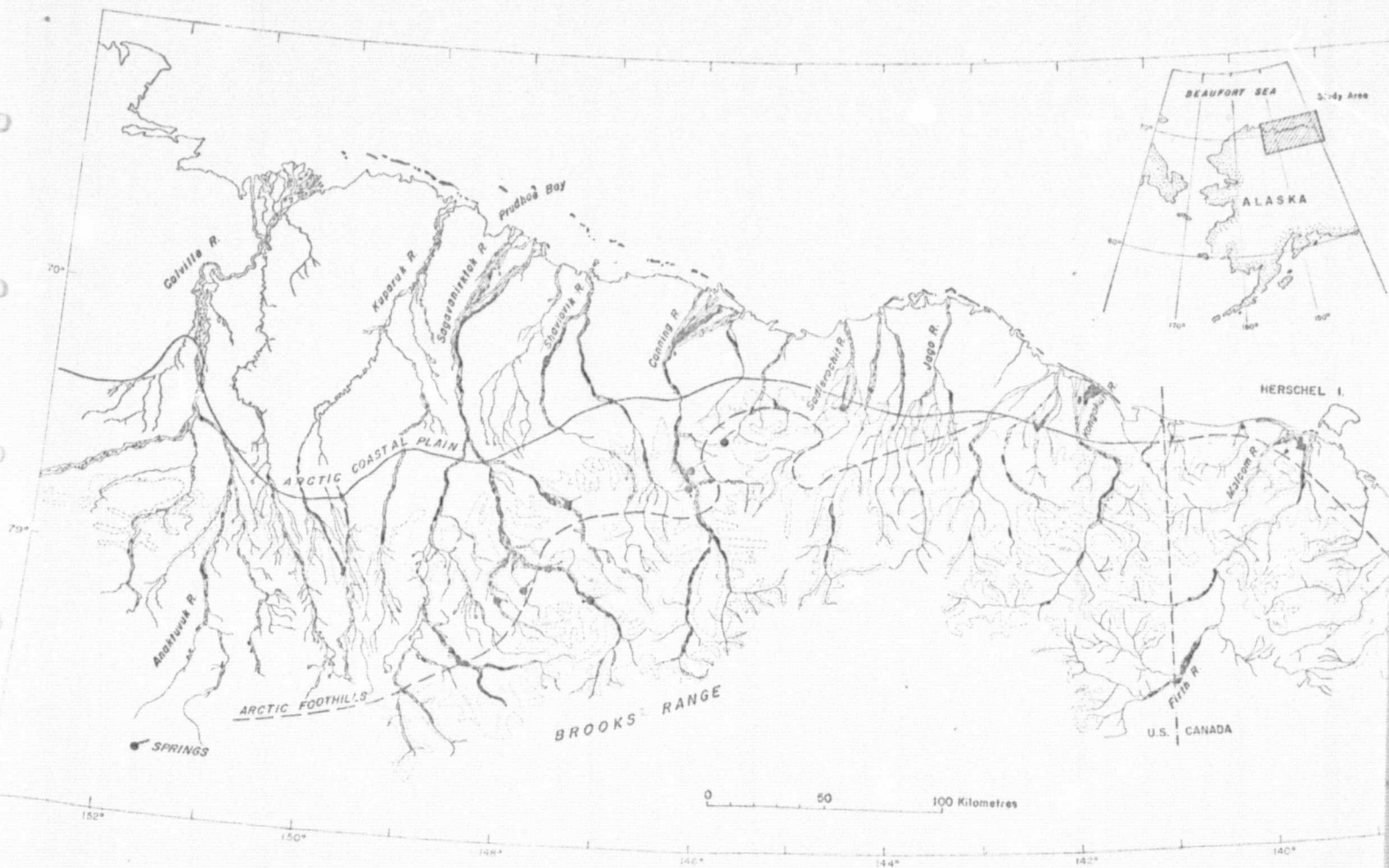


Figure 2. Distribution of naleds in northeastern Alaska from Landsat imagery. Contours in metres. Spring locations from Childers, Sloan, and Meckel (1973).



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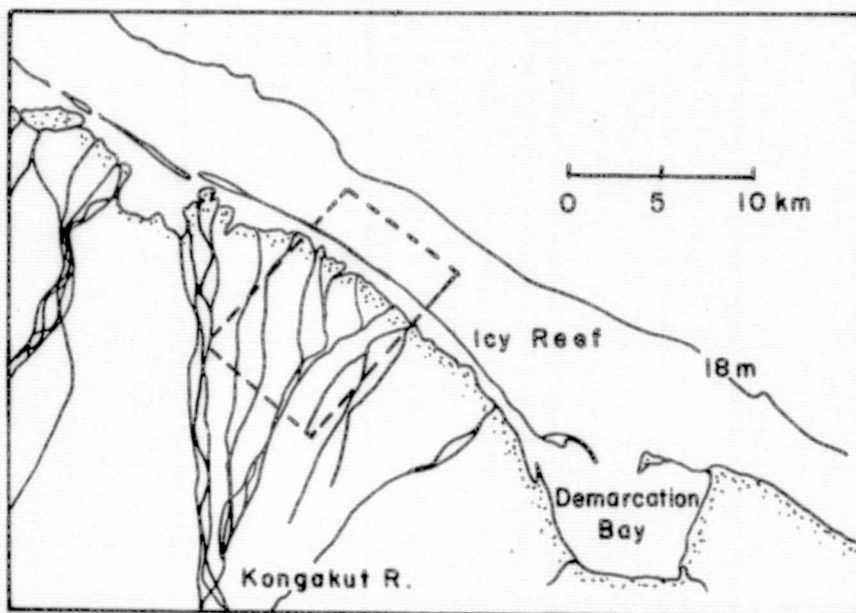


Figure 4. Naled on Kongakut River Delta, near international boundary,  
August 2, 1973. (Photo courtesy of Andrew Short, Louisiana  
State Univ., Inst. of Coastal Studies).

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stream channel or in an alluvial layer above the permafrost or bedrock, it will continue to flow as long as water is supplied to the system. If flow is sufficiently restricted, as by a sudden change in stream gradient, or by a decrease in the permeability or thickness of the channel fill, water is forced upward over the river ice. Continuing or subsequent overflows build sheets of fresh ice over the original naled surface. The total thickness may reach 5 to 6 metres under such conditions (Péwé, 1973; Williams, 1953, 1970).

#### Methods

Imagery from the multispectral scanner (MSS) of the Landsat-1 Satellite was used to delineate naleds on the North Slope of Alaska and adjacent areas of Canada. Our study area extends from the coast to about 200 km inland. Imagery was received from late July 1972 through the fall of 1973, except during the polar night (mid-October through late February). Thus, it was possible to monitor one seasonal cycle of river icing and to compare naled remnants during August and September 1972 with those of 1973.

Satellite imagery covered the study area at 18-day intervals. Overlap of successive images often provided three consecutive days of coverage of a given location. However, since delineation of ground features is dependent on the absence of cloud cover, the frequency of observations was often limited by weather conditions.

Each image covers an area approximately 100 nautical miles (185 km) square at a scale of about 1:1,000,000. This scale enables us clearly to identify naleds larger than about 300 metres square. Smaller naleds are discernible when high contrast between ice and tundra or water and snow exists.

The scanner operates in four spectral bands: band 4, 500-600 nm (green), band 5, 600-700 nm (red), band 6, 700-800 nm (visible-near IR), and band 7, 800-1100 nm (near IR). One image is taken in each band for every satellite pass.

During the summer months, bands 4 and 5 show the greatest contrast between the naleds, the unfrozen channels, and the surrounding tundra. On these images, naleds appear white, channels and deltas are light toned, and the higher ground a darker shade (Figs. 7a, d). During the winter, band 7 shows the greatest contrast between the naleds and the snow-covered tundra and stream channels (Fig. 7b). In these images fresh ice or water appears dark and the surrounding terrain white, except where relief is sufficient to produce shadows.

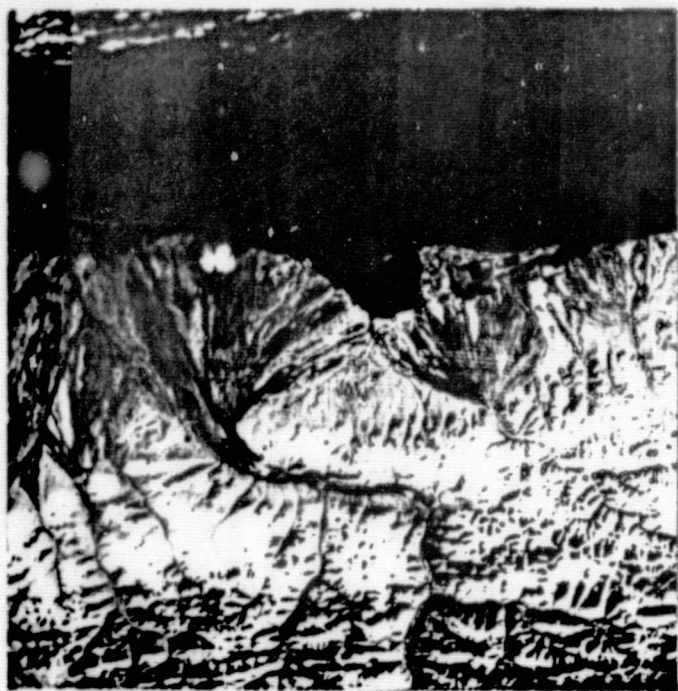
Additional information was available from a high-altitude U-2 flight of 21 June, 1974 (NASA Flight No. 74-101). This flight utilized a RC-10 camera with color infrared film at a flight altitude of 65,000 ft (19.9 km) on flight lines north and south over the Sagavanirktok River and east and west across the middle of the Arctic Coastal Plain.

#### Distribution of Naleds

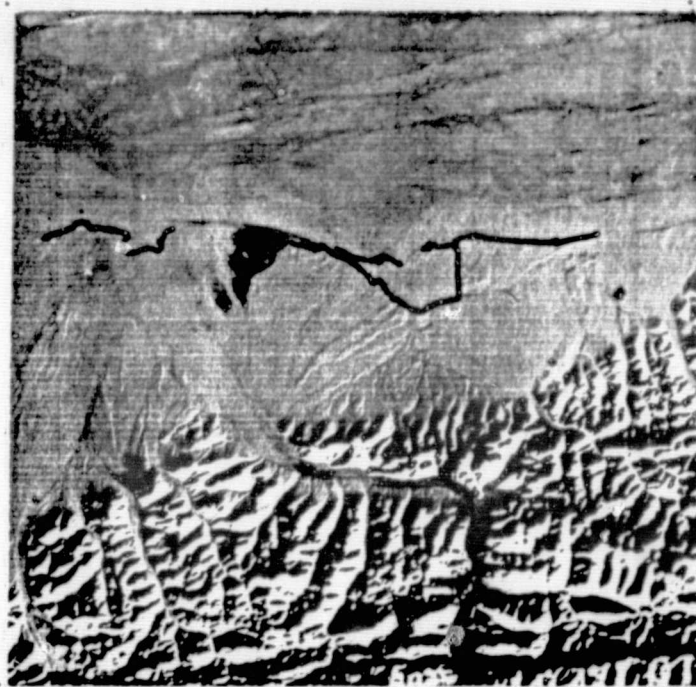
River naleds detectable on Landsat-1 imagery during late winter are shown in Figure 2. The Colville River is the largest river in the study area. A cursory inspection of imagery of rivers west of and including the lower Colville showed almost no naleds, with the exception of a possible naled along the Ikpihpuk River (approximately 155°W long), about 40 km from the coast (for example, see image 1257-21463).

East of the Colville River, most of the larger streams between the Anaktuvuk and Firth Rivers show naleds in the Foothills Province (Fig. 2).





a. 11 SEPT 72



b. 08 MAR 73



c. 06 JUNE 73



d. 05 SEPT 73

Figure 7. Comparative Landsat imagery of the naleds on the Kongakut River Delta, September 1972 through September 1973. Landsat images no. 1050-20541, 1228-20435, 1318-20476, 1409-20475.

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The larger deltas also commonly show naleds. Fewest naleds occur in the reaches between the foothills and the river mouths.

The downstream ends of naleds are diffuse and feathery, presumably because surface flow continues downstream for varying distances after initial overflow. These downstream tails may extend for considerable distances and interconnect naleds. For instance, the Canning River shows almost one continuous naled from the Brooks Range to within about 10 km of its mouth (Figs. 2 and 3).

The distribution of naleds shows good correlation with that of the shallow reaches of braided streams (Figs. 2 and 4). Naleds may be the cause or the result of the braiding. During summer, the elevated surfaces of naled remnants may divert channels around ice patches. Once formed, the shallow channels readily freeze down to the bottom, creating conditions favorable to blocking the underflow and forcing overflow. On the other hand, low-altitude aerial photographs show channels dissecting naleds subsequent to spring flooding (Figs. 4 and 5), indicating that naleds do not always cause stream diversion.

A comparison of known perennial springs (Childers et al., 1973) with the sites of river naleds shows that all of the springs correspond to locations of naleds (Fig. 2). Naleds may indicate other unmapped springs, especially in areas with no apparent upstream water sources (Williams and Van Everdingen, 1973). Presumably, perennially flowing springs exist at or upstream from such naleds.

#### Development of Naleds

Landsat imagery from mid-September to the shut-off of the cameras for the arctic night in late October 1972 does not show new naled development.

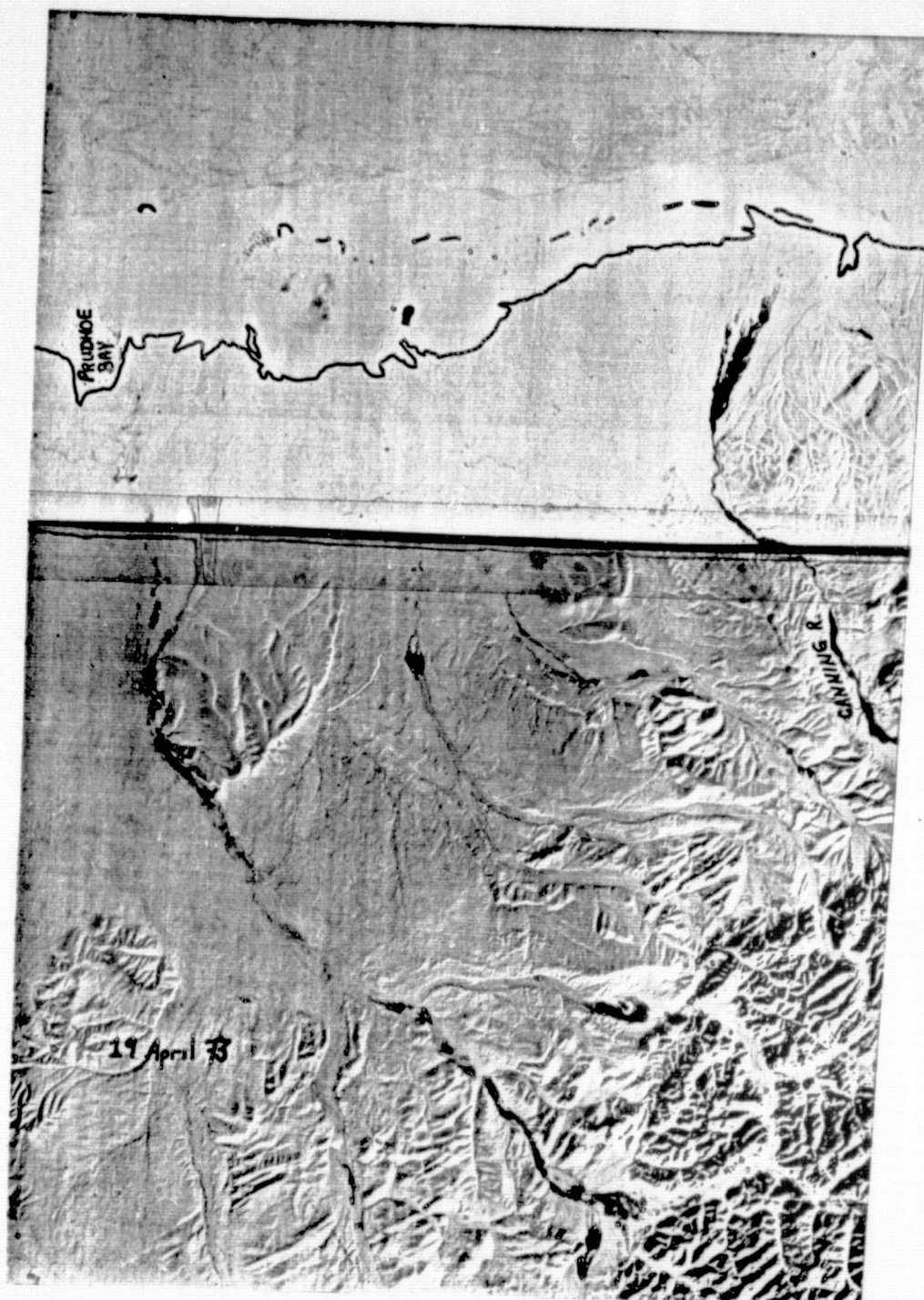


Figure 3. Naleds on lower Canning and Sagavanirktok Rivers on April 19, 1973. Landsat images no. 1270-21175 and 1270-21181.

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Many rivers were still flowing at this time, indicating that the basic requirements of an initial ice cover and water flow barrier had not yet been met.

During the period from the first 1973 imagery in early March until spring breakup in June, many naleds increased in size. However, some were apparently unchanged throughout this part of winter, indicating that their water sources were cut off, had greatly decreased flow, or were frozen prior to March.

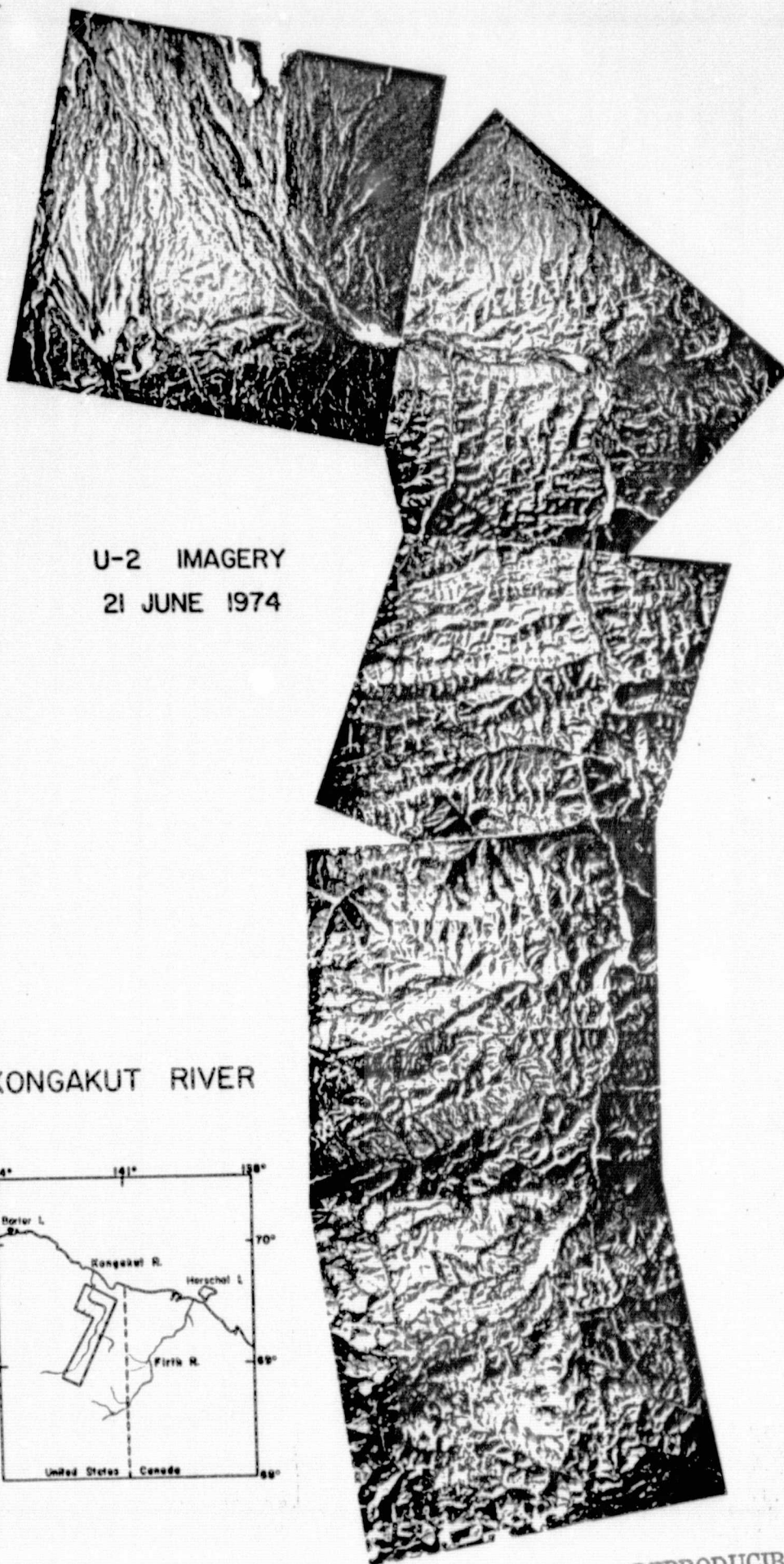
During the first week of August 1973, weather conditions permitted excellent coverage of most of the study area by Landsat imagery. At this time, remnants of most of the larger naleds are visible (for example image numbers 1376-21112, 1378-21164, 3 and 5 August). They are considerably less extensive than the winter naleds, and some undoubtedly melted before autumn freeze-up. The largest naleds of the previous winter, such as on the Kongakut-Sagavanirktok and Canning Rivers, still had remnants in September (for example image numbers 1410-20533, 1414-21162). It is probable that these large naleds persist for more than one season under favorable conditions. Such naleds would result in lower ground temperatures below than in adjacent terrain not covered by reflecting ice during summer. This would in turn promote early icing in the following winter. Thus, long-lived naleds may be self-perpetuating.

#### Naleds on the Kongakut River

The delta of the Kongakut River (Kangikat on some charts) located in the Arctic Wildlife Refuge (Fig. 2) repeatedly came to our attention during the icing study. Naleds on this river are particularly large (Figs. 4 and 5) and long lived. The delta ice buildup commonly extends

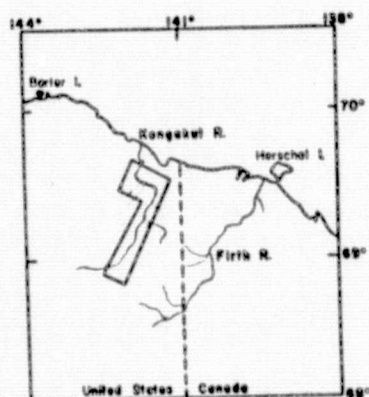
Figure 5. U-2 photographic mosaic taken June 21, 1974, of naleds along the Kongakut River.





U-2 IMAGERY  
21 JUNE 1974

# KONGAKUT RIVER



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into the lagoon seaward of the delta front and out to Icy Reef. This interaction of river icing with the marine environment and delta front is unique along the Alaskan coastline.

Icy Reef was named by the Franklin expedition in August 1826, when heavy ice outside the reef necessitated dragging boats over the mudflats at the mouth of the Kongakut River to Beaufort Lagoon (Leffingwell, 1919). Leffingwell's description thus indicates that the name did not result from the extension of naleds into the lagoon.

Naleds were present on the delta throughout the year of our Landsat coverage (Figs. 6 and 7). During the winter of 1972-73 the naleds increased in size (Figs. 6c,d), starting sometime after September and continuing through March, 1973. (April and May images were cloudy). Beginning with the start of the thaw season in late May and continuing until mid-August, the naleds shrank to about one-tenth their former extent (Figs. 6e,f,g,h, and 7c,d). It appears that the delta naled was unchanged from mid-August to mid-September, 1973 (Figs. 6a,b,h,i).

During the winter of 1973, the naled extended into the lagoon in front of the delta (Figs. 6c,d; 7b). An image obtained about two weeks after the initiation of river flow (Figs. 6e and 7c) indicates that naleds remained in the lagoon through the flooding period. Field observations during August 1972 and September 1973, as well as the Landsat imagery shown in Figures 6g,h,i and 7a, d showed no ice in the lagoon during these periods. Low altitude imagery in early August 1973 (Fig. 4) shows naled ice on the delta front abutting the lagoon. During field operations in late August of 1971, ice was observed in the lagoon behind Icy Reef. According to the Coast Pilot (U.S. Dept. Commerce, 1964), ice is commonly present in the lagoon behind Icy Reef throughout the summer.

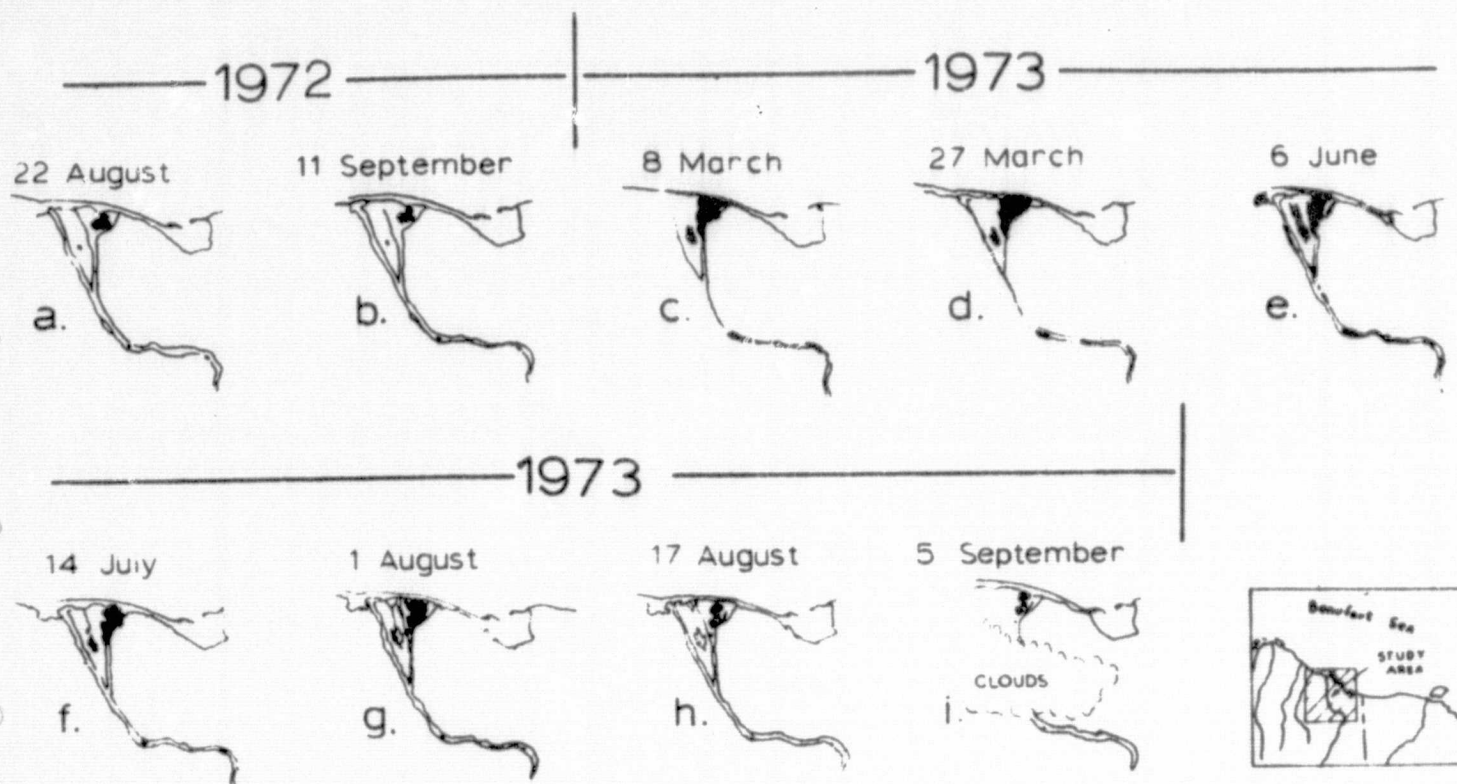


Figure 6. Development and decay of the delta and lagoon naled on the Kongakut River Delta. Data from Landsat images no. 1308-20424, 1050-20541, 1228-20435, 2147-20493, 1318-20426, 1356-20542, 1374-20541, 1390-20423, 1409-20475.

In trying to explain the lagoon ice seen in 1971 and reported in the Coast Pilot, we considered that the coastline may have retreated very recently off the Kongakut River, and that permafrost may be near the surface of the lagoon, thereby enhancing the summer occurrence of ice by lowering the water temperature in the lagoon. A comparison of Leffingwell's (1919) map of the coastline, which is quite accurate in most areas, with the modern maps, suggests such a retreat of the coastline over a period of about 35 years. However, further investigations of aerial photography taken during the past 20 years and modern coverage suggest that the early maps are in error and that the coastline is rather stable.

It has become apparent from the study of Landsat imagery that river icing is an important factor influencing the marine processes along the delta front of the Kongakut River. A comparison of 1972 and 1973 imagery in mid-August and early September shows little difference in the size of the Kongakut River naled, although channel patterns on it are somewhat different (Figs. 6a,b,h,i; 7a,d). In years following extensive icing the lagoon in front of the delta remains ice-covered through the summer. The fact that naleds on the delta last through the summer makes them the logical sites for icing during the succeeding winter.

#### Climate and Naleds

In order to assess the effect of weather conditions on the size of naleds, monthly rainfall and snow accumulation data for the nearest weather station (Barter Island) were analyzed for 1971, 1972 and 1973 (U.S. Dept. Commerce, 1971-1973).

Heavy summer precipitation would presumably promote icing during the following winter by creating an abundant ground water supply. In

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contrast, the insulating effect of heavy snowfall during the early winter would decrease the growth rate of river ice cover, thus producing unfavorable icing conditions. Heavy snow cover late in the winter may extend the period of icing by preserving lower temperatures in the ground, but according to Carey (1973), this insulating effect is less important than rain and snow conditions during the preceding summer and early winter.

During the two seasons studied, the influence of varied summer precipitation was apparently balanced by opposing snowfall conditions. Precipitation was much greater than average during the summer of 1971 and below average the following summer season. Groundwater conditions would therefore have been more favorable for naled development during the winter of 1971-72 than in the following winter. On the other hand, snowfall was heavier during the early winter of 1971 than during the same period in 1972, which would have insulated the ground and led to less favorable icing conditions in 1971-72. Finally, snowfall during late winter was greater in 1972 than in 1973, which would have been more favorable to 1971-72 icing.

Because of the contrasting and balancing climatic influences during 1971-1973, it is not possible to evaluate the impact of climate on naled growth with our present information. There appears to have been no significant difference in the area of naleds remaining during the two summers of Landsat observations (Figs. 6b,i; 7a,d). In order to assess the variability in weather and icing conditions, several more seasons would have to be studied. Furthermore, considering the abundance of springs in the Arctic, the influence of seasonal variation in precipitation patterns

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on spring and groundwater flow needs to be evaluated. Spring discharge may be relatively constant from season to season and from year to year owing to reservoir storage. Furthermore, there may be a considerable time lag between recharge of the reservoir and spring discharge.

#### Discussion

Naleds on the North Slope of Alaska are widespread but are concentrated east of the Colville River, at the heads of deltas, and where streams leave confined mountain channels. The Colville River has few naleds and almost none along the lower thirds of its course. One might assume that there is continuous flow to the sea along the channel under the ice or within the river bed. The work of Walker and others (Arnborg and others, 1966; Walker, 1974) has indicated that the delta channels are below sea level and are connected to the sea, even at the maximum ice growth. Walker's work also shows that saline water extends upstream for 60 km below the ice cover. This would suggest either that there is no continuous source of water in the drainage basin of this large system, or that the river flow is so greatly reduced in volume and force that it can be accommodated in a thin layer between the ice and an intruding salt water wedge. Measurements at three locations along the lower Colville above the delta showed no flow in April 1975 (Joe Childers, U.S. Geological Survey, personal comm., 1975). This and the apparent lack of springs along this river (Fig. 2) suggests that there may be virtually no winter freshwater flow in the Colville River system. This would be significant in any search for a year-round water supply.

Pumping from a river with little or no winter recharge could result in salt water intrusion, or the depletion of stagnant freshwater pools.

Pumping down of freshwater pools in March 1976 for the Prudhoe Bay Oil Field Complex from the Sagavanirktok and Kuparuk Rivers has already forced overwintering fish to retreat to isolated pockets within the river bed (Terry Bendock, Alaska Department of Fish and Game, personal comm., 1976). The Sagavanirktok River has numerous naleds (Fig. 2) suggestive of year-round water recharge, although the water depletion rate by pumping near Prudhoe suggests little or no flow reaches this far downstream in late winter.

Naleds influence the ground temperature, permafrost, and channel form in such a way as to favor the continued development of naleds at the same locations. In the long summer days, when ground temperatures are raised and the surficial thaw layer is formed, much of the incoming solar energy is reflected from the naled surface. Therefore, ground temperatures would be lower and the active layer above the permafrost thinner in the immediate vicinity of naleds. This in turn would enhance icing in the same area during the following freeze season.

The morphology of North Slope streams where icing occurs is strongly influenced by the naled masses. Spring flooding and subsequent flow are consequent upon the relief surface present in the spring. Thus, under some conditions much of the spring floodwater is initially forced to detour around elevated naled surfaces, causing the channels to widen. Consequently, most of the braided sections of streams and rivers shown in Figure 2 are probable locations of recent or present-day naleds. Once formed, the braided channels are favorable sites for continued icing. The wide shallow flow favors rapid freezing to the bottom in the fall and early winter.



Naleds on the deltas appear to be dissected readily by the seasonal river flow (Fig. 4), although the location of the dissection may differ from year to year (Figs. 6b,c; 7a,d). Floodwaters are often high enough to overtop the naled. The flow then seeks low areas within the naled that form the forerunners of dissecting channels.

Naleds that extend into the lagoon off the delta of the Kongakut River are bounded on the seaward side by Icy Reef, a barrier beach (Figs. 4, 6 and 7). New lagoon ice floats during the fall freezeup; however, where it is depressed by naled tails as winter proceeds, it rests on the bottom. Subsequently, a mound of ice develops, covering the delta and lagoon (Fig. 6c). During the flooding of the river, water flowing over this mound will bypass the delta and lagoon to a point beyond the barrier island. Since most of the river sediment load is transported at this time (Walker, 1974), the sediments will also bypass the delta and lagoon.

During glacial episodes along the arctic coast of Alaska, the climate was colder and dryer (Hopkins, 1967). Thus, it is presumed that less surface water would have been available, the flow season would have been shorter, and the depth of winter freeze greater. The latitudinal depression of isotherms suggests that naleds of the type found in the Arctic today would probably have been more widespread at lower latitudes. Naleds along the arctic coast would have been unaffected in areas where thermal springs exist. In general, naled development would probably have been enhanced by the shorter thaw season and the greater probability that naleds would last

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from one year to the next, but hindered by the lesser amounts of precipitation.

The map of naleds (Fig. 2) is also a map of potentially useful freshwater sources. The map may also serve as a guide in the planning of future construction, which might interact with the hydrologic regime to create problems. Naled areas indicate nearby springs that are overwintering sites for some fish species (Childers and others, 1973) and are therefore important in the biological regime of the Arctic. The scarcity of naleds west of the Colville River suggests limited water resources or extensive unimpeded groundwater flow. Considering the importance of developing a water supply in the Arctic, further investigation in this area is needed.

### Conclusions

1. Naleds on the North Slope of Alaska are widespread but are concentrated east of the Colville River, primarily where the streams leave the confined mountain channels and at the heads of deltas.
2. Some larger naleds can last through the summer melt season to form the nucleus of naleds that grow during the following years, although channels commonly dissect the naleds during the melt season.
3. The deflection of spring floods around naleds may commonly cause shallow braided channels to develop.
4. Some naleds are, and others may be, the site of groundwater discharge in the form of springs. They are thus potential sources of year-round fresh water.
5. Precipitation patterns should affect icing patterns unless naleds are fed by bedrock springs. The major controlling climatic factors tended to cancel each other in the two years studied, and the influence is as yet unknown.

### Acknowledgments

We are grateful to David Hopkins, Joe Childers, and Charles Sloan for critical reading of the manuscript and for expanding our knowledge of naleds through their expertise, and thank Tau Rho Alpha for preparing Figure 1. This work was supported by NASA contract S-70243AG to utilize Landsat-1 imagery.

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## Figure Captions

- Figure 1. Physiographic diagram of study area. Diagram by Tau Rho Alpha.
- Figure 2. Distribution of naleds in northeastern Alaska from Landsat imagery. Contours in metres. Spring locations from Childers, Sloan, and Meckel (1973).
- Figure 3. Naleds on lower Canning and Sagavanirktok Rivers on April 19, 1973. Landsat images no. 1270-21175 and 1270-21181.
- Figure 4. Naled on Kongakut River Delta, near international boundary, August 2, 1973. (Photo courtesy of Andrew Short, Louisiana State Univ., Inst. of Coastal Studies).
- Figure 5. U-2 photographic mosaic taken June 21, 1974, of naleds along the Kongakut River.
- Figure 6. Development and decay of the delta and lagoon naled on the Kongakut River Delta. Data from Landsat images no. 1308-20424, 1050-20541, 1223-20435, 2147-20493, 1318-20426, 1356-20542, 1374-20541, 1390-20423, 1409-20475.
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